LIGHT-WEIGHT NUCLEAR PROPULSION APPLICATIONS TO HIGH PERFORMANCE NAVAL SHIPS

Randolph M. Brooks

LIGHT-WEIGHT NUCLEAR PROPULSION

APPLICATIONS TO HIGH PERFORMANCE

NAVAL SHIPS

by

RANDOLPH M. BROOKS

B.S., U.S. Naval Academy

(1969)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE

DEGREE OF OCEAN ENGINEER

AND FOR THE DEGREE OF

MASTER OF SCIENCE IN NUCLEAR ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May, 1976

LIGHT-WEIGHT NUCLEAR PROPULSION APPLICATIONS
TO HIGH PERFORMANCE NAVAL SHIPS
by
RANDOLPH M. BROOKS

Submitted to the Department of Ocean Engineering and the Department of Nuclear Engineering on May 7, 1976, in partial fulfillment of the requirements for the degrees of Ocean Engineer and Master of Science in Nuclear Engineering.

ABSTRACT

The future generation of naval high performance ships, such as the Surface Effect Ship and Hydrofoil, suffer from the fact that they are invariably endurance limited. Although a nuclear propulsion plant could resolve this problem, current naval pressurized water reactor systems including collision bulkheads and increased weight for foundations and electrical propulsion machinery translate into too great a specific propulsion weight for utilization on weight limited high performance ships. Through the utilization of parametric weight models, the limits of nuclear specific propulsion weight as a function of ship type, displacement, payload weight fraction and speed was determined. Having established these limits, nuclear propulsion systems which might be suitable for high performance ships were investigated and their corresponding specific propulsion weights were estimated. The potential of these systems was then predicted for the high performance ships in terms of payload weight fraction, speed and displacement.

Thesis Supervisor: Clark Graham
Title: Associate Professor of Marine Engineering

ACKNOWLEDGEMENTS

The author wishes to express his sincere gratitude to the United States Navy for the opportunity of pursuing the course of studies at MIT that has led to this thesis.

To many individuals such as Ben Friedman and John A. Satkowski at the Office of Naval Research, James L. Schuler at the Naval Sea Systems Command and Professor Philip Mandel at MIT, the author is grateful for background material and suggestions; to Professor David D. Lanning and most especially Professor Clark Graham, the author wishes to give thanks for offering much good guidance.

But most especially, to my wife Debby, goes my special thanks for her patient encouragement and in translating this into a legible manuscript.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

In October, 1973, with the flare-up of the Arab-Israeli conflict, the fossil-fueled Sixth Fleet of the U. S. Navy, although able to admirably discharge its responsibilities, (M1) felt the Achilles Heel of being tied to a hydrocarbon umbilical cord. So it was really no great surprise when on August 5, 1974, House Bill No. 14592 was signed into law by Congress.

The statute (Figure 1),commonly referred to as Title VIII, has the naval ship design and acquisition community in a turmoil due to the fact that current pressurized water reactor (PWR) system weight limits the smallest conventional displacement ship, with current payload weight fractions, to approximately 8500 tons. Therefore, if the Navy abides by the letter of the law, there will be few if any small, austere ships--and cost is a direct function of size. This then has grave implications if the U. S. Navy is to achieve its stated floor of 600 ships by 1985 with present fiscal restraints.

Against the background of this ship size-nuclear propulsion plant weight dilemma has been the emergence of the naval high performance ship technology which seeks to maximize ship speed even in high sea states. Through the utilization of high performance ship standards (i.e. very low specific machinery box weight, austere habitability standards, increased automation, low ship hull structural density, low specific electrical weight, essential manning concepts coupled with "mother ship" supported Integrated Logistic Support, and fitted-to-ship weight optimized payloads), such ships as the surface effect ship (SES), hydrofoil, and other promising

FIGURE 1 (R1)

TITLE VIII-NUCLEAR POWERED NAVY

10 USC 7291 note. 88 STAT. 408 88 STAT. 409	Sec. 801. It is the policy of the United States of America to modernize the strike forces of the United States Navy by the construction of nuclear powered major combatant vessels and to provide for an adequate industrial base for the research, development, design, construction, operation, and maintenance for such vessels. New construction major combatant vessels for the strike forces of the United States Navy authorized subsequent to the date of the enactment of this Act becomes law shall be nuclear powered, except as provided in this title.
"Major combatant vessels for the strike forces of the United States Navy." 10 USC 7291 note.	Sec. 802. For the purposes of this title, the term "major combatant vessels for the strike forces of the United States Navy" means -- (1) combatant submarines for strategic or tactical missions or both; (2) combatant vessels intended to operate in combat in aircraft carrier task groups (that is, aircraft carriers and the cruisers, frigates, and destroyers which accompany aircraft carriers); and (3) those types of combatant vessels referred to in clauses (1) and (2) above designed for independent combat missions where essentially unlimited high speed endurance will be of significant military value.
Report to Congress. 10 USC 7291 note. 64 STAT. 832 84 STAT. 1169. Department of Defense Five Year Program.	Sec. 803. The Secretary of Defense shall submit to Congress each calendar year, at the same time the President submits the budget to Congress under section 201 of the Budget and Accounting Act, 1921 (31 U.S.C. 11), a written report regarding the application of nuclear propulsion to major combatant vessels for the strike forces of the United States Navy. The report shall identify contract placement dates for their construction and shall identify the Department of Defense Five Year Defense Program for construction of nuclear powered major combatant vessels for the strike forces of the United States Navy.
10 USC 7291 note.	Sec. 804. All requests for authorizations or appropriations from Congress for major combatant vessels for the strike forces of the United States Navy shall be for construction of nuclear powered major combatant vessels for such forces unless and until the President has fully advised the Congress that construction of nuclear powered vessels for such purpose is not in the national interest. Such report of the President to the Congress shall include for consideration by Congress an alternate program of nuclear powered ships with appropriate design, cost, and schedule information.

lift/buoyancy sustension hybrids have shown calm water speed up to 100 knots and high sustained speeds up to sea state 6. As Mandel has noted (M1) however, gains in speed have been due to the reduction in specific machinery box weight rather than improvements in the lift to drag ratio.

Although with the advent of aircraft derivative gas turbines, the small high performance ship has achieved viability, for this fossil-fueled ship there still remain disadvantageous tradeoffs that must be made between displacement, range, speed, and payload weight fraction. In particular, high performance ships are endurance limited, i.e. their "staying" capability is low. Only a light weight nuclear propulsion plant can provide the combination of unlimited endurance and high speed so tactically desirous.

The idea of light weight nuclear reactors is not a new one. However, with any technology, the movement of events must be at times just right for a concept to come to fruition. Admiral Rickover's Naval Reactors Program has marched up a measured ladder in developing the pressurized water reactor, building the first sodium cooled system, investigating gas-cooled and organic cooled reactors, introducing natural circulation, and leading numerous reactor advances, all aimed at maintaining safe, reliable, rugged, maintainable plants. With a small, tightly controlled cadre of manpower, the Admiral has then had primarily to concentrate upon meeting short term requirements, upon immediate engineering and product management, and upon absorbing fleet lessons. Thus Naval Reactors has questioned the long lead time, cost, and effort required to make step changes as opposed to orderly progressions, particularly when studies have shown that most proposed light-weight reactor concepts would necessitate relaxed standards

in ship quieting, redundancy, maintenance area, shock standards, and particularly in safety, i.e. shielding, loss of coolant or depressurization accidents, flooding, etc. It should be emphasized that it is this rugged, reliable, safe record of Naval Reactors that has made the reactor such a dominant force in the first place.

Outside of Naval Reactors, the U. S. Air Force and U. S. Navy investigated light-weight reactors for use on airplanes in the early 60's but eventually lost Congressional backing since shielding weight constraints coupled with the safety of an airborne vehicle brought the program to a halt. Westinghouse and Los Alamos Laboratory also developed light-weight reactors for the Nerva and Rover nuclear programs, but these reactors were only designed for a reactor lifetime of one hour. Although some very generalized work in a Navy study called Project 2000 studied the future directions of naval high performance ship platform design and propulsion technology, there has not been an in depth analysis of light-weight nuclear propulsion plant applications to high performance ships.

The objectives of this study therefore became:

- Determine if there is a need for light-weight nuclear reactors
- Determine the specific propulsion weight limits for installing nuclear propulsion plants in various high performance ships
- Determine if there are any particular nuclear propulsion plants that might be successfully utilized on high performance ships and the necessary tradeoffs to effect this integration
- Determine if there is a "best" nuclear propulsion system and "best" high performance ship to recommend for concentrated Research and Development effort

•Determine if a small high performance ship with a nuclear propulsion plant would be more cost beneficial in terms of the tactical benefits and number of ships it might replace through expanded area coverage

To realize these objectives, this analysis will, after examining the need for light-weight nuclear propulsion plants, especially on high performance ships, determine the limits of nuclear propulsion weight as a function of ship type, displacement, payload weight fraction, and speed. After establishing these limits, possible nuclear propulsion systems and their corresponding specific propulsion weights will be estimated. The potential of these systems will then be investigated in terms of payload weight fraction, speed, and displacement. Possible tradeoffs to achieve light-weight nuclear plants will then be suggested and a method for further light-weight propulsion plant evaluation elucidated.

CHAPTER 2

THE REQUIREMENT FOR LIGHT-WEIGHT NUCLEAR PROPULSION PLANTS

The purpose of this section is to firmly establish the need for light-weight nuclear propulsion plants. This will be done by examining the evolving technology of high performance ships and examining their endurance limitations. The current nuclear propulsion plant weight limits will then be explored to determine if a light-weight reactor is indeed warranted.

2.1 Historical Prespective

Throughout the history of seapower, assessing technological break-throughs correctly and seizing the initiative has been essential. For instance, John Hawkins and his cousin and protégé Francis Drake forsake contempory thought and pressed for Queen Elizabeth's fleet to be built as floating anti-ship gun platforms emphasizing speed and mobility, contrary to the popular boarding and lofty fore-and-aftcastle designs of the day. Though a certain proportion of Great Ships were built to overawe the enemy and for close work when it could not be avoided, the flush decked (or nearly flush decked), low freeboard ship of three or more beams length with an increasing amount of long culverins which could throw a 17-pound ball 1¼ miles became standard in the Queen's Navy. It was a technological assessment that contributed to victory over the Spanish Armada in 1588 and marked the rise of England as a leading sea power (P6).

Assessments can backfire, too, though. Following the year the USS Wampanoag attained the maximum speed of 17.75 knots and the sustained speed of 16 knots on her trials (the fastest time for a self-propelled ship up to 1868), a board headed by Rear Admiral L. M. Goldsborough recommended

that the ship be redesigned to carry more sail power at the expense of her steam power. Furthermore, the Secretary of the Navy issued a general order requiring that all ships of the Navy except tugs and dispatch ships be fitted with full sail power. The Wampanoag and her sister ship Ammonoosuc were condemned as unfit for naval service and laid up. The Goldsborough board also recommended that four-bladed screws be replaced with less efficient two-bladed screws which could be lined up vertically with the keel to reduce drag when under sail. (P6).

The saga of the marriage of the nuclear reactor and the submarine and the enhancement of its capability through the Polaris missile are modern examples of accurate technological assessments. Now with the advent of the high performance ship -- accurate, timely assessments must be made.

2.1.1 Operational Realities

Continued U. S. global responsibilities and reduced "friendly" logistic bases dictate that highly independent, fast reaction sea power be maintained. Unfortunately, however, present naval ships are primarily low speed, burst capability ships tied to a hydrocarbon umbilical cord.

Although present nuclear powered ships are invariably high displacement, high cost ships, their tactical benefits as listed below are unquestionable.

1. Virtually unlimited endurance at high speeds which gives:
   - (a) increased tactical flexibility and freedom of independent action
   - (b) capability to cycle in high speed transit to and from distant and less vulnerable sources of ammunition, aviation fuel, and other supplies needed to continue in action

2. Reduced vulnerability due to:

   (a) freedom from dependence upon replenishment in areas of high threat

   (b) improved capability for sealing ship against nuclear, biological, and chemical attack

   (c) enhanced opportunity to use evasive transit tracks

3. Significantly reduced dependence upon logistic support giving:

   (a) decreased requirement for mobile support forces

   (b) reduced requirements for fuel at bases and prepositioned at depots

4. Greater attack effectiveness due to:

   (a) ability to be on attack station a higher percentage of time

   (b) increased ability to exploit weather conditions

5. Reduced maintenance effort on hulls of ships and aircraft by elimination of corrosive stack gases (R1)

2.1.2 Technological Implications

One of the hopes for better ship cost effectiveness is through expanded area coverage by increasing sustained speeds. As the sustained speed available to a ship increases, the number of ships required for tasks ranging from ASW barrier patrol to sonobuoy distribution decreases, the investment in a given force size goes down, and the number of escort ships per task force group or element is smaller. This is an intriguing concept if a high sustained speed, highly independent ship with good payload could be built. For even if this ship were to cost more than a conventional counterpart, which it most certainly would, the speed advantage would allow it to be a more cost beneficial ship. This would be true, especially

if it were a small ship which reduced the biggest fiscal culprit -- manpower.

Certain technological developments seem to be pushing the feasibility of high performance ships. Among these are the following:

(1) Evolving experience in design, production, and fabrication of low hull structural density materials such as aluminum and titanuim

(2) Development of electronic automatic height sensing devices which enable the fully submerged foil angle of attack to be rapidly varied in anticipation of ocean wave motion

(3) Development of low specific machinery box weight gas turbine plants

(4) Continued development of light, adaptable superconducting generators and motors

(5) Development of light-weight planetary gear systems

(6) Continued work on supercavitating propellers and foils

(7) Continued effort in reducing specific electrical weight through 400 H_z systems

(8) Evolution of certain drag reduction vehicles through novel sustension means that can maintain high speeds in high sea states

These so called high performance ships which offer such great advantages, however, do not have "stay" capability as will be seen in Section 2.3.

2.2 Applications of High Performance Ships

One method popularly utilized in classifying different ship forms is by identification of the sustention forces. As shown by Jewel (J1), the sustension forces can be illustrated in the form of an equilateral triangle with the vertices representing the pure forces (Figure 2):

x vertex -- unpowered static lift (buoyancy)

y vertex -- powered dynamic lift (foils)

z vertex -- powered static lift (air cushion)

As can be noted in the triangle, conventional displacement ships, hydrofoils, and air cushion vehicles are representative of single lift force vehicles at the x, y, and z vertices respectively, of the sustension triangle. Mixture lift force vehicles can be noted such as the 10% buoyant lift, 90% foil dynamic lift Large Hydrofoil Hybrid Ship (LAHHS) at (1,9,0) and the 10% buoyant lift, 90% air cushion lift Surface Effect Ship (SES) at (1,0,9).

The incentive for advanced marine vehicles has been the ever present operational commander's desire for more speed, better seakeeping, or a combination of both. As opposed to an evolving threat scenario which "pulls" most conventional displacement ship evolutions, technological breakthroughs such as reduction in specific machinery box weight through marinized aircraft derivative gas turbines and increased experience with low hull structural density materials such as Al - 5086 have "pushed" the high speed marine vehicle. However, it should be remembered that destroyer type hull forms such as the famous Farragut class succeeded in attaining speeds in the 35 - 40 knots range some 40 years ago. The limiting factor then, as it has continued to be for existing naval ships, has been sea-

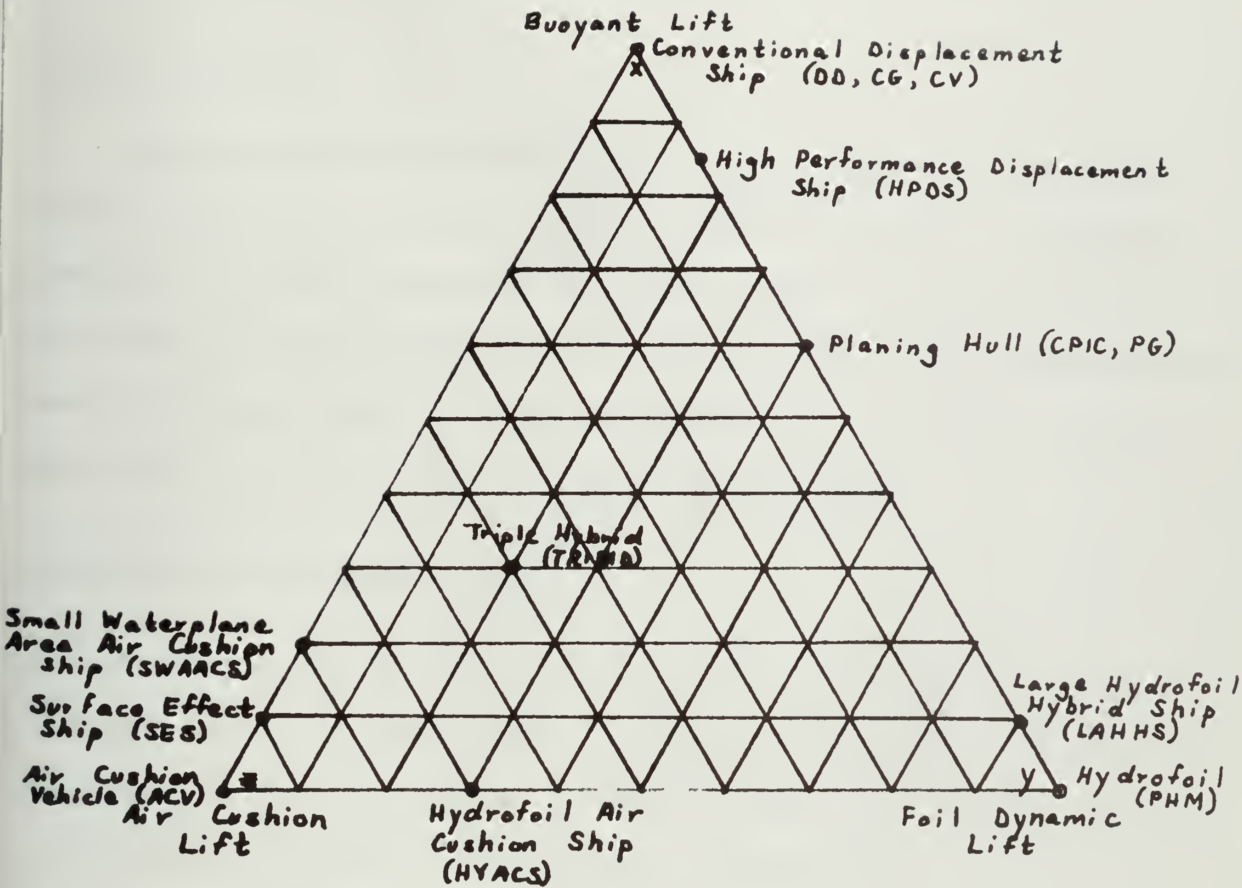


FIGURE 2 The Sustension Triangle (J1)

kindliness, i. e. deck wetness, slam induced structural fatigue limits, and motion habitability limitations. The following subsections explain certain unique features of particular high performance ships that currently combine high speed and improved seakeeping. (Appendix A includes tabulated characteristics of various naval ship types).

2.2.1 Hydrofoils

This dynamic foil lift vehicle can retain its speed into high sea states because the hull is decoupled from the sea surface. Its seaway response is largely governed by the design length of the foil struts and the specific type of dynamic control system employed. Preliminary designs such as the DEH and HOC have been extrapolated for ocean escort service and a 230 ton PHM has been built for NATO utilization.

2.2.2 Surface Effect Ship (SES)

The Surface Effect Ship is a captured air bubble vehicle with hard sidewalls and bow and stern seals. Two types are actively being studied, the low l_c/b_c SES and the high l_c/b_c SES (l_c and b_c are cushion length and beam respectively). For a constant cushion density $W_G/\sqrt{A_c}$,

where W_G = gross weight of SES (lbm)

$$A_c = l_c \cdot b_c \ (ft^2)$$

a high l_c/b_c SES manifests lower total drag in the lower speed regime since wavemaking drag is the predominant drag. Around 60 knots, however, depending on the displacement, the low l_c/b_c SES manifest a lower drag since frictional drag becomes predominant. A 2200 ton low l_c/b_c SES

is being contemplated for possible production and testing.

2.2.3 Small Waterplane Area Twin Hull (SWATH)

The major nonconventional characteristic of this ship is its small waterplane area which moves the main box hull away from the waterline thus reducing ship motion due to wave action. The submerged hull provides an excellent sonar platform and the dual stern is ideal for twin screw propulsion. These features combined with the large platform area make the concept very attractive for a small escort ship with air capabilities.

2.2.4 Air Cushion Vehicle (ACV)

The ACV as distinguished from the SES does not have hard piercing sidewalls. Rather, in line with its projected amphibious and Arctic roles, it employs either peri-cell skirts or bag and finger skirts, and shrouded air propellers. Amphibious ACVs, known as the JEFF A and JEFF B, are currently being built to carry a 60 ton payload at 50-knots in sea state two with a 25-knot headwind on a 100° F day.

2.2.5 High Performance Displacement Ship (HPDS)

This semi-planing low c_B, high l/b Series 64 displacement monohull differs primarily from other conventional displacement ships in that it is designed to hydrofoil (HOC) design criteria and standards. (Appendix B details the difference in design criteria between hydrofoils and various surface ships.) By utilizing hydrofoil design standards, Grostick (G1) showed that a displacement hull form of similar size to a hydrofoil would carry more payload and has the same speed and endurance as the hydrofoil at high speeds and a greater endurance at lower speeds. Thus the foil

system weight may be traded for payload and/or speed when hydrofoil standards are utilized for displacement ship design. A preliminary design to verify these theoretical results is ongoing at M. I. T. (B7).

2.2.6 High Performance Hybrids

There are also combinations of sustension systems such as the Large Hydrofoil Hybrid/Ship (LAHHS) and the Small Waterplane Area Air Cushion Ship that are currently being evaluated since they provide better platforms capabilities than "pure" vehicles and eliminate certain size limitations which exist presently such as for the hydrofoil. These vehicles are still in the conceptual design phase (M6).

2.3 Fossil-Fueled Ship Parametric Relationships

Depending on the ship displacement, maximum speed, and design criteria and standards utilized, the weight fraction which can be allocated for fuel and the propulsion system is constrained. The weight fraction required for the propulsion system is established once the type of propulsion plant to be utilized is determined. This is due to the fact that the particular plant type delineates a specific machinery weight. Therefore, since the particular ship displacement and maximum speed delineate the specific power, the propulsion weight fraction is fixed as shown below and in Figure 3.

$$\frac{GP2\ WT}{\Delta} = \frac{GP2\ WT}{SHP} \cdot \frac{SHP}{\Delta} \cdot \frac{1}{2240} \qquad (2.1)$$

where GP2 WT = weight of propulsion machinery

SHP = installed shaft horsepower

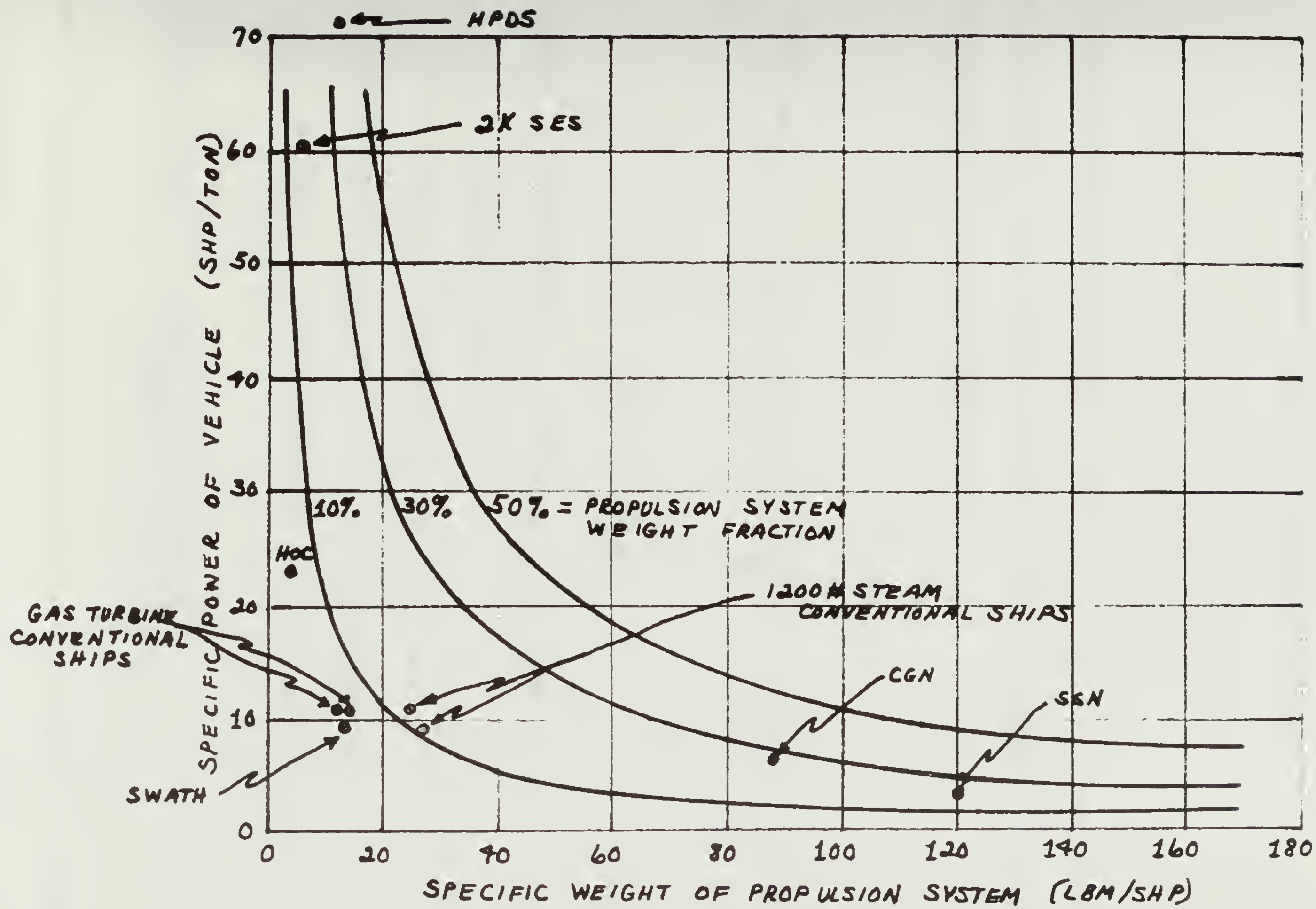


FIGURE 3 SPECIFIC POWER VS SPECIFIC MACHINERY WEIGHT

Δ = full load displacement of ship (tons)

and $\frac{GP2\ WT}{\Delta}$ = propulsion system weight fraction (dimensionless)

$\frac{GP2\ WT}{SHP}$ = specific machinery weight (lbm/shp)

$\frac{SHP}{\Delta}$ = specific power (shp/ton)

Since high performance ships require high specific power, for a certain propulsion plant weight fraction, this translates into low specific machinery weights, i.e. gas turbine plants.

$$\frac{GP2\ WT}{SHP} \propto 1\Big/\left(\frac{SHP}{\Delta}\right) \qquad (2.2)$$

Furthermore, and equally important, this also means that endurance is reduced.

$$E = \frac{W_f}{\Delta} \cdot \frac{\Delta}{SHP} \cdot \frac{2240}{SFC} \qquad (2.3)$$

where E = endurance at an endurance speed (hrs)

W_f = weight of fuel (tons)

Δ = full load displacement of ship (tons)

SHP = shaft horsepower for an endurance speed

SFC = specific fuel consumption at an endurance speed (lbm/shp hr)

or $$\left(\text{Endurance}\right)\left(\begin{matrix}\text{Specific}\\ \text{Power}\end{matrix}\right) = \frac{\text{Fuel Weight Fraction}}{\text{Specific Fuel Consumption}} \qquad (2.4)$$

Since present technology limits SFC to 0.5 ± 0.2 lbm/shp hr at endurance speed due to inherent thermal cycle limits, using SFC=0.5lbm/shp hr in

Equation 2.4 yields:

$$\begin{pmatrix}\text{Endurance}\\ \text{in hours}\end{pmatrix}\begin{pmatrix}\text{Specific Power}\\ \text{in Hp/Ton}\end{pmatrix} = 4480\begin{pmatrix}\text{Fuel Weight}\\ \text{Fraction}\end{pmatrix} \qquad (2.5)$$

Therefore, if the fuel weight fraction is fixed, endurance varies inversely with specific power.

$$E \propto 1\Big/\left(\frac{SHP}{\Delta}\right) \qquad (2.6)$$

Recalling that range is endurance times speed, estimates of range for differing ship types can be determined.

$$R = E \cdot V \qquad (2.7)$$

where R = range (nm) at endurance speed V (kts)

Substituting Equation 2.7 into Equation 2.3 yields:

$$R \cdot \frac{SHP}{\Delta \cdot V} = \frac{W_f}{\Delta} \cdot \frac{1}{SFC} \cdot 2240 \qquad (2.8)$$

where $\frac{SHP}{\Delta \cdot V}$ = specific resistance or transport efficiency $\left(\frac{\text{shp}}{\text{ton kt}}\right)$

$\frac{W_f}{\Delta}$ = fuel weight fraction (non-dimensional)

If specific resistance is non-dimensionalized and as before 0.5 lbm/SHP-hr is substituted for SFC:

$$\frac{SHP}{\Delta \cdot V} = \frac{6.87}{PC} \cdot \frac{V}{L/D} \cdot \frac{1}{V} \qquad (2.9)$$

$$(\text{Range in nm})\begin{pmatrix}\text{Specific}\\ \text{Resistance}\end{pmatrix} = 652\begin{pmatrix}\text{Fuel Weight}\\ \text{Fraction}\end{pmatrix} \qquad (\ .10)$$

where PC = propulsive coefficient = EHP/SHP

D = drag force at velocity V

L = lift force (static, dynamic, buoyant, thrust)

EHP = effective horsepower (horsepower actually getting into water)

Estimates of endurance and range for typical ship types using Equation 2.4 and 2.7 are shown in Table 1.

TABLE 1

ESTIMATED RANGE AND ENDURANCE FOR TYPICAL VEHICLES

Typical Vehicle	Speed (Kts)	Specific Power (HP/Ton)	Fuel Fraction	Estimated Endurance (Hr)	Estimated Range (nm)
Hydrofoil cruising	44	50.	0.30	27.	1,200
Low l_c/b_c SES Cruising	49	30.	0.30	45.	2,200
Destroyer Top Speed	34	20.	0.25	56.	1,900
CV Top Speed	35	3.	0.10	150.	5,200
Destroyer Cruising	20	3.	0.25	370.	6,500
CV Cruising	18	0.5	0.10	900.	16,000

This is an overly simplistic analysis particularly with respect to dynamic lift vehicles since drag changes as fuel is burned off.

$$\frac{dW}{dt} = -(SFC)(SHP) \tag{2.11}$$

where W = instantaneous ship weight (lbm)

$$\int_{W_G}^{W_{empty}} \left(\frac{W}{SHP}\right) \frac{dW}{W} = \int_0^E -(SFC)\, dt \tag{2.12}$$

where W_G = ship gross weight (lbm)

$$W_{Empty} = W_G - W_f$$

$$dR = V\, dt \quad \text{and} \quad R = \int_0^E V\, dt \tag{2.13}$$

Assuming V is a fixed velocity and SFC and W/SHP are constants at that velocity

$$E = \frac{1}{SFC} \cdot \frac{W}{SHP} \cdot \ln\left(\frac{1}{1 - W_f/W_G}\right) \tag{2.14}$$

$$R = \frac{V}{SFC} \cdot \frac{W}{SHP} \ln\left(\frac{1}{1 - W_f/W_G}\right) \tag{2.15}$$

$$SHP = \frac{D_E \cdot V}{325\,(PC)(n_T)} \tag{2.16}$$

where D_E = equivalent drag in lbm (including lift power)

This so called Brequet correction alone means that for a fuel weight fraction of 0.30, the range is 19% greater than for the non-Brequet approach. Furthermore, high performance vehicles are generally more nearly operating at their most efficient speeds at top speeds as opposed to conventional ships whose drag curve rises directly with speed increase. However, for very general trends, as shown in Figures 4 and 5, there is a strong tendency for reduced range for high performance ships.

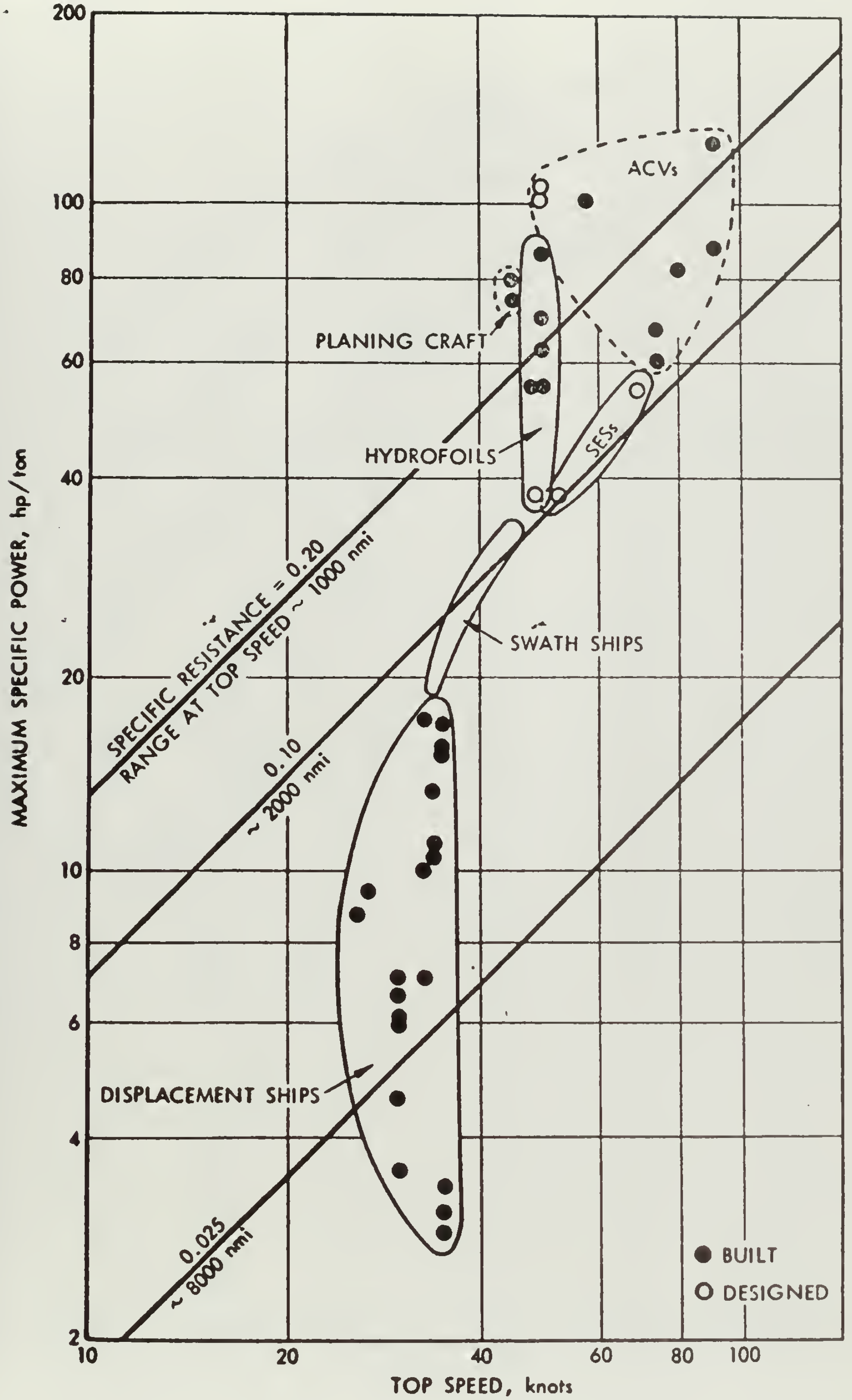


FIGURE 4 Specific Power and Specific Resistance for Navy Ships (R3)

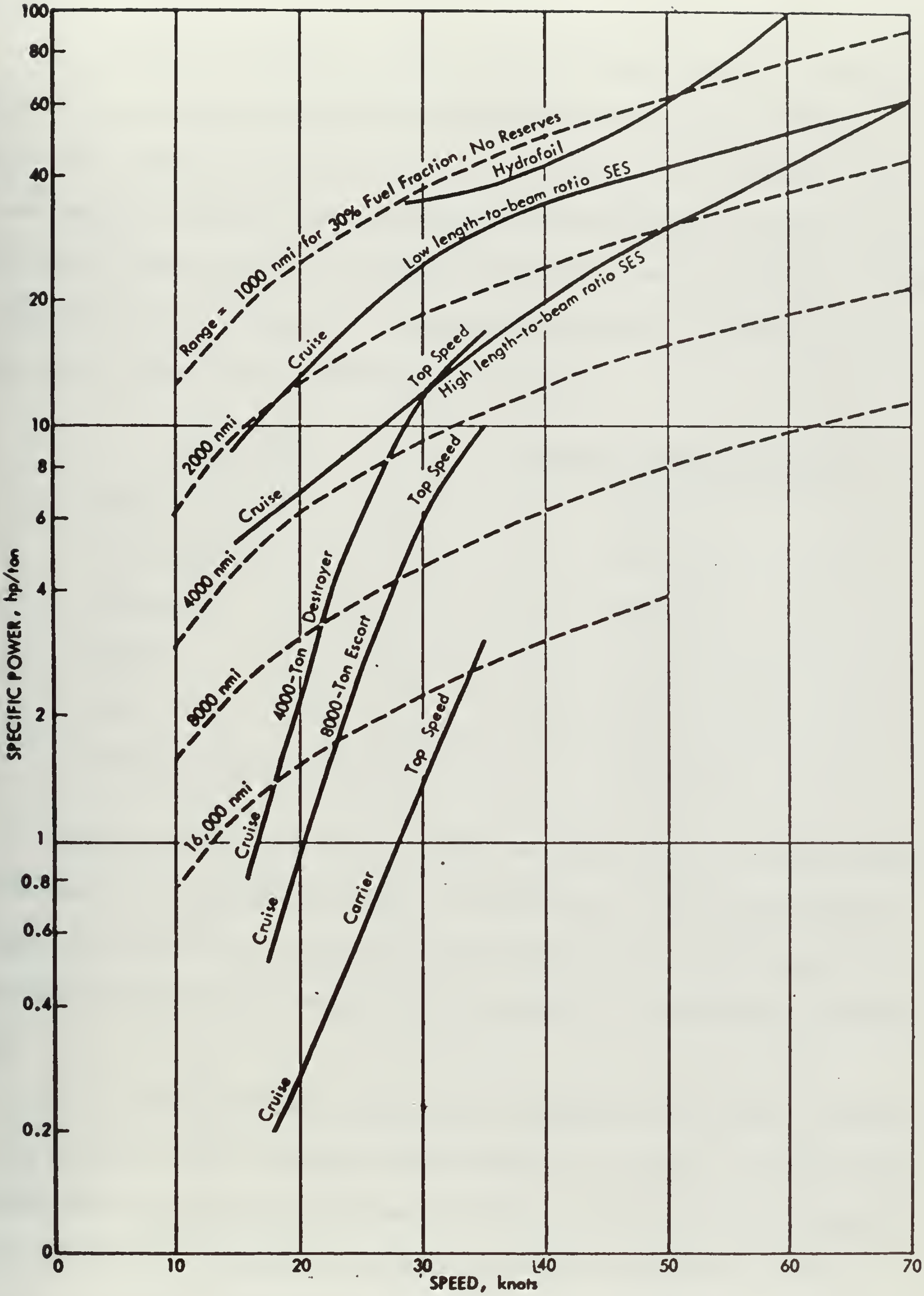


FIGURE 5 Specific Power/Range Relationships for Navy Ships (R3)

It should be pointed out that in the preliminary design, there are also certain technological limits which also presently limit the displacement parameter as shown in Table 2. Furthermore, if the specific resistance for particular vehicle types and displacement are plotted as a function of speed, the most efficient speeds can also be bracketed. Figure 6 demonstrates for various 1000 ton displacement high performance ships, the most efficient speed domains are as follows:

SHIP TYPE	MOST EFFICIENT SPEED (KTS)
High l_c/b_c SES	25 - 50
Low l_c/b_c SES	70 - 100
Hydrofoil	35 - 45
SWATH	20 - 30
ACV	60 - 80
Planing Hull (300 ton)	55 - 65

Then since the displacement, speed, and range all are in some manner constrained, the payload will also be constrained. It then essentially becomes a tradeoff for a particular fossil-fueled ship type designed to certain standards between endurance and payload for a constrained displacement.

At this point payload weight should adequately be defined. Payload in the context of this analysis is the portion of the ship's displacement attributable to its primary military mission, excluding mobility factors. Using the Ship Work Breakdown Structure System Classification (N1) as defined in Table 3, payload then is command and surveillance (Weight Group 4), armament (Weight Group 7), and those items in the variable load directly

TABLE 2

SHIP SIZE CONSTRAINTS

VEHICLE	MAX SIZE (TONS)	LIMITING PROBLEMS
Hydrofoil	1500-2000	a) Foil weight Problems b) Wing loading due to cavitation
ACV	1000	a) Excessive structural weight fraction b) For air propulsion, size of propellers
SES low l_c/b_c	5000	a) Cushion pressure limits
high l_c/b_c	Unknown	b) l_c/b_c ratio limited by structural considerations
HPDS	Unknown	a) Structural limits of low hull structural density materials
SWATH	Unknown	a) Structural limits

Conventional Displacement Ship	No Practical Limits Exist (Except Cost)
Air Ship	
Submarine	

FIGURE 6 Specific Resistance vs. Speed for High Performance Ships (E1)

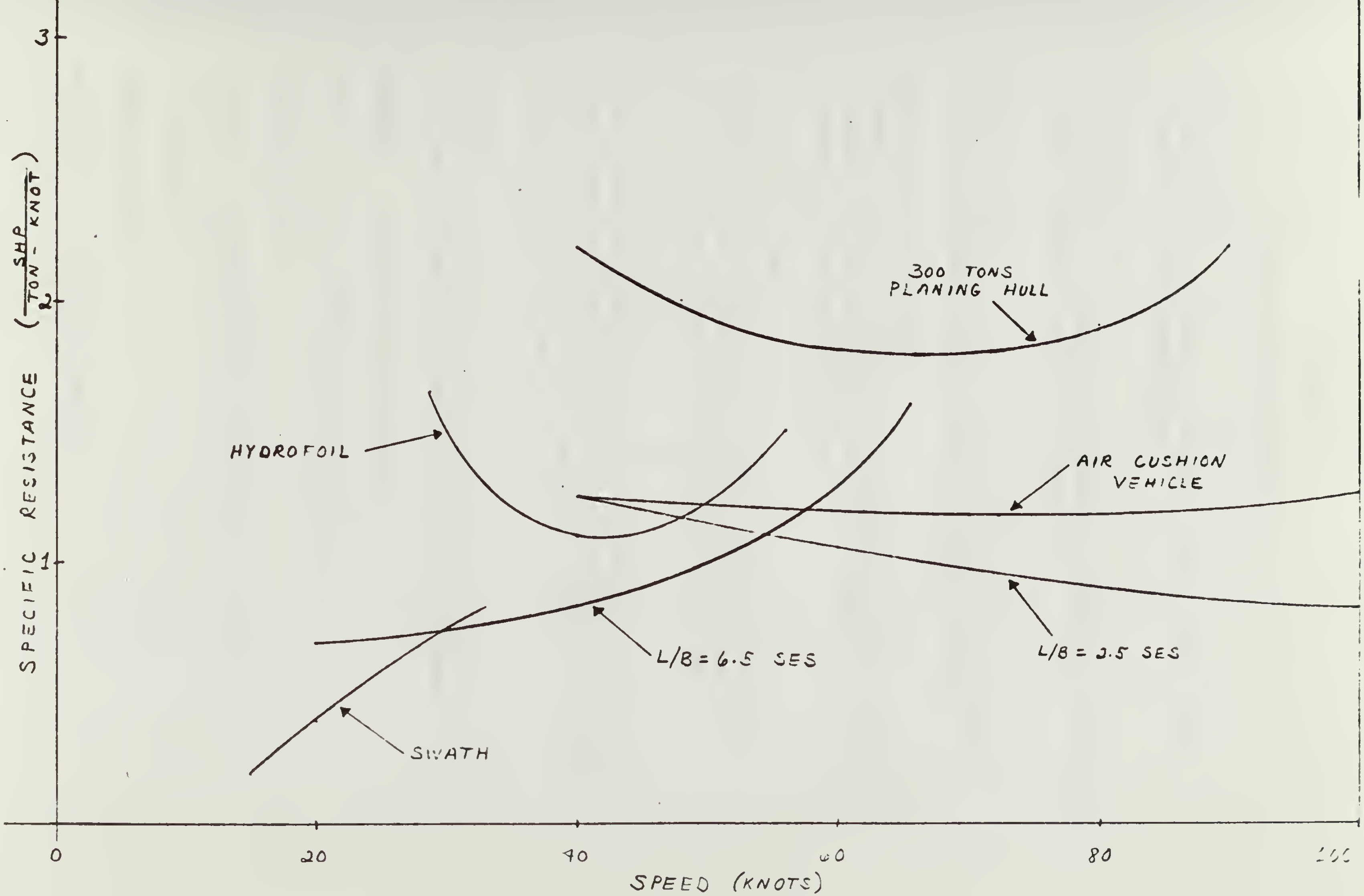


TABLE 3

WEIGHT CLASSIFICATIONS (N1)

Group 1	Hull Structure Framing, Shell Plating, Bulkheads, Decks, Deck House Structure, Masts, Foundations
Group 2	Propulsion Plant Prime Movers, Transmission Systems, Propulsors, Propulsion Support Systems (Fuel Oil & Lube Oil)
Group 3	Electric Plant Power Generation Systems, Power Distribution Systems, Lighting System, Power Generation Support Systems
Group 4	Command and Surveillance Command & Control Systems, Navigation Systems, Exterior Communications, Surface & Subsurface Sensors, Countermeasures, Fire Control Systems
Group 5	Auxiliary Systems Heating, Ventilation & Air Conditioning Systems, Seawater Systems, Freshwater Systems, Anchor, Mooring & Boat Handling Systems, Foil Systems & Controls
Group 6	Outfit and Furnishings Non-Structural Compartmentation, Painting, Insulation, Deck Covering, Messing, Berthing & Sanitary Facilities, Furnishings and Fixtures, Commissary Equipment, Office Furnishings, Storeroom Fixtures
Group 7	Armament Gun Systems, Missile Launching Systems, Torpedo Launching Systems, Ammunition Stowage and Handling Systems
Loads	Personnel - Crew and Crew's Effects Stores - Fresh, Frozen and Dry Foodstuffs General Stores - Fuel Oil - For Main Propulsion, Power Generation Lubricating Oil - Potable Water - Ammunition - For Ship's Weapons

Aircraft - Aircraft Weight Only

Aviation Stores - Repair Parts and Tools for Aircraft Maintenance

Aviation Fuel -

related to the military mission; ammunition, aircraft, and aircraft related stores.

2.4 Current Nuclear Propulsion Weight Limits

The design tradeoffs would be greatly simplified if a virtually unlimited endurance nuclear propulsion plant could be installed on all naval ships. Unfortunately weight problems complicate the situation.

2.4.1 Description of the Naval Pressurized Water Reactor

The naval pressurized water reactor system consists of a nuclear reactor core contained in a pressure vessel; a primary coolant system which removes the heat generated in the core and transfers it to the secondary, or steam system; a steam machinery plant for propulsion and electric power generation; and radiation shielding. The primary coolant system consists of one or more loops, each having one or more coolant pumps, a steam generator (boiler), a pressurizing vessel, and connecting piping with appropriate valves.

Since the coolant water becomes radioactive in passing through the reactor core, radiation shielding is required around the portion of the plant which contains radioactive coolant in order to protect personnel. A separate reactor shield surrounds the pressure vessel; this shield provides sufficient attenuation of the direct radiation from the reactor core to permit access to the reactor compartment when the reactor is shut down.

The steam produced in the separate secondary circuit by the heat exchanger is nonradioactive, therefore, the steam propulsion machinery need not be shielded. This machinery and the necessary auxiliaries for

electric power generation, control, and other functions are arranged in a conventional way in the engine room and auxiliary machinery rooms, outside the reactor compartment.

2.4.2 Comparative Analysis of Similar Cruiser Classes: Nuclear vs Fossil-Fueled

To determine the ship impact of the naval pressurized water reactor system an examination of similar cruiser classes was made. The CG-16 (USS Leahy) was compared to the CGN-25 (USS Bainbridge) and the CG-26 (USS Belknap) to the CGN-35 (USS Truxton). These choices were made based on the fact that the CG-16 and CGN-25 are similar in size, mission area capabilities, and designed and built during the same time frame, as were also the CG-26 and CGN-35. The one major difference is that the CG-16 and CG-26 each have four 1200# boilers; CGN-25 and CGN-35 each have two D2G(GE) pressurized water reactors. Since the mission area, i.e. payload, is essentially the same, the reactor system weight impact should be evident if normalized in terms of specific propulsion weight (lbm/SHP).

Comparing the propulsion system weights (Group 2) reveals that the nuclear version has a specific machinery box weight of ~90 lbm/SHP as opposed to ~25 lbm/SHP for the fossil-fueled version. In addition, the fossil-fueled cruiser has about 48 lbm/SHP devoted to fuel to attain a 8000 nautical endurance at 20 knots, which somewhat equalizes the weights between the nuclear and fossil-fueled cruisers. However, there are other weight increases also necessitated on the nuclear version.

In addition to the basic nuclear propulsion plant, weight must also be devoted to structural/collision bulkheads to protect the reactor, foundation, weight increases to support the very dense reactor, and increased

electrical plant weight to support the nuclear plant ~ 30 lbm/SHP. When all this is accounted for the total impact becomes:

$$\delta_o = \frac{\text{Overall Group 2 Weight}}{\text{SHP}} = \frac{\text{Group 2 Weight}}{\text{SHP}} + \frac{\text{Group 1' Weight}}{\text{SHP}}$$

$$+ \frac{\text{Group 3' Weight}}{\text{SHP}} \approx 120 \text{ lbm/SHP} \qquad (2.17)$$

where Group 1' Weight = increased weight of structural/collision bulkheads and foundations for a nuclear ship

Group 2' Weight = propulsion machinery weight

Group 3' Weight = increased weight required to support reactor

δ_o = overall specific propulsion weight

$\frac{\text{Group 2 Weight}}{\text{SHP}} = \delta_2 =$ specific machinery weight

$\frac{\text{Group 1' Weight}}{\text{SHP}} = \delta_{1'} =$ specific hull weight increase

$\frac{\text{Group 3' Weight}}{\text{SHP}} = \delta_{3'} =$ specific electric weight increase

For the fossil-fueled ship $\delta_{1'}$ and $\delta_{3'} \longrightarrow 0$, i.e. $\delta_o = \delta_2$ for fossil-fueled ships and $\delta_o = \delta_2 + \delta_{1'} + \delta_{3'}$ for the nuclear ship. This definition will hold throughout the remainder of the thesis. Table 4 summarizes the results.

TABLE 4

CRUISER PROPULSION SPECIFIC WEIGHT SUMMARY

	FOSSIL-FUELED CRUISER	NUCLEAR POWERED CRUISER
δ_2	25	90
Fuel/SHP	48	0
δ_1'	0	30
δ_3'	0	
δ_0	25	120
$\delta_0 + \frac{\text{Fuel}}{\text{SHP}}$	73	120

Therefore, to accurately compare two similar ships, one fossil-fueled and one nuclear powered, it is necessary to consider the overall specific propulsion weight in any analysis. As can readily be seen, the nuclear plant forces increases in foundation weight, increased weight for collision/structural bulkheads and increased weight in the electrical plant to support the reactor which totals $\sim$ 30 lbm/SHP, a specific weight about twice the specific machinery box weight of the entire gas turbine plant on the FFG - 7 ($\sim$15 lbm/SHP).

2.5 Viable Ship Platforms for Investigation

After a general parametric examination of high performance ships, it has been seen that fossil-fueled high performance ships such as the surface effect ship and hydrofoil require high specific powers and low specific propulsion weights. For fixed fuel weight fractions, endurance varies inversely with specific power, therefore high performance ships are endurance limited, i.e. they have low "stay" capability. A nuclear propulsion plant would obviously solve the problem. However, examination of current naval pressurized water reactor weights reveal that the machinery box weight, collision/structural bulkheads weight, increases in propulsion foundation weight, and increases in electrical machinery weight directly in support of the nuclear plant translates into an overall specific propulsion weight of about 120 lbm/SHP. This weight is too heavy for high performance ships which are quite weight limited.

However, if light weight nuclear propulsion systems could be designed, the problem could be alleviated. In the next chapter the following will be examined:

- Since the conventional displacement ship is a proven platform, investigate the conventional displacement ship to determine the impact of improved weight reactor systems
- Investigate the high performance displacement ship since it will show the impact of high performance technology
- Investigate the hydrofoil since its ability to attain high speeds up to sea state 6 offers unquestionable tactical advantages
- Investigate the low l_c /b_cSES since it offers the greatest speed capability

The SWATH and hybrid high performance ships will not be considered due to the state of this technology. Furthermore, the air cushion vehicle will be eliminated from consideration due to its envisioned operating area, i.e. amphibious operations which demand short ranges and increases the vulnerability of a reactor propulsion system.

CHAPTER 3

SHIP CONSTRAINTS OF NUCLEAR PROPULSION PLANT DESIGN

A computerized sensitivity analysis was made to determine in a more analytical manner the effects of displacement, speed, range, and specific propulsion weight on payload weight for certain fossil-fueled and nuclear conventional and high performance ships. The conventional displacement ship was analyzed to serve as an existing benchmark against the more unknown qualities of the high performance ships. Domains were determined for installing nuclear plants on these ships in terms of

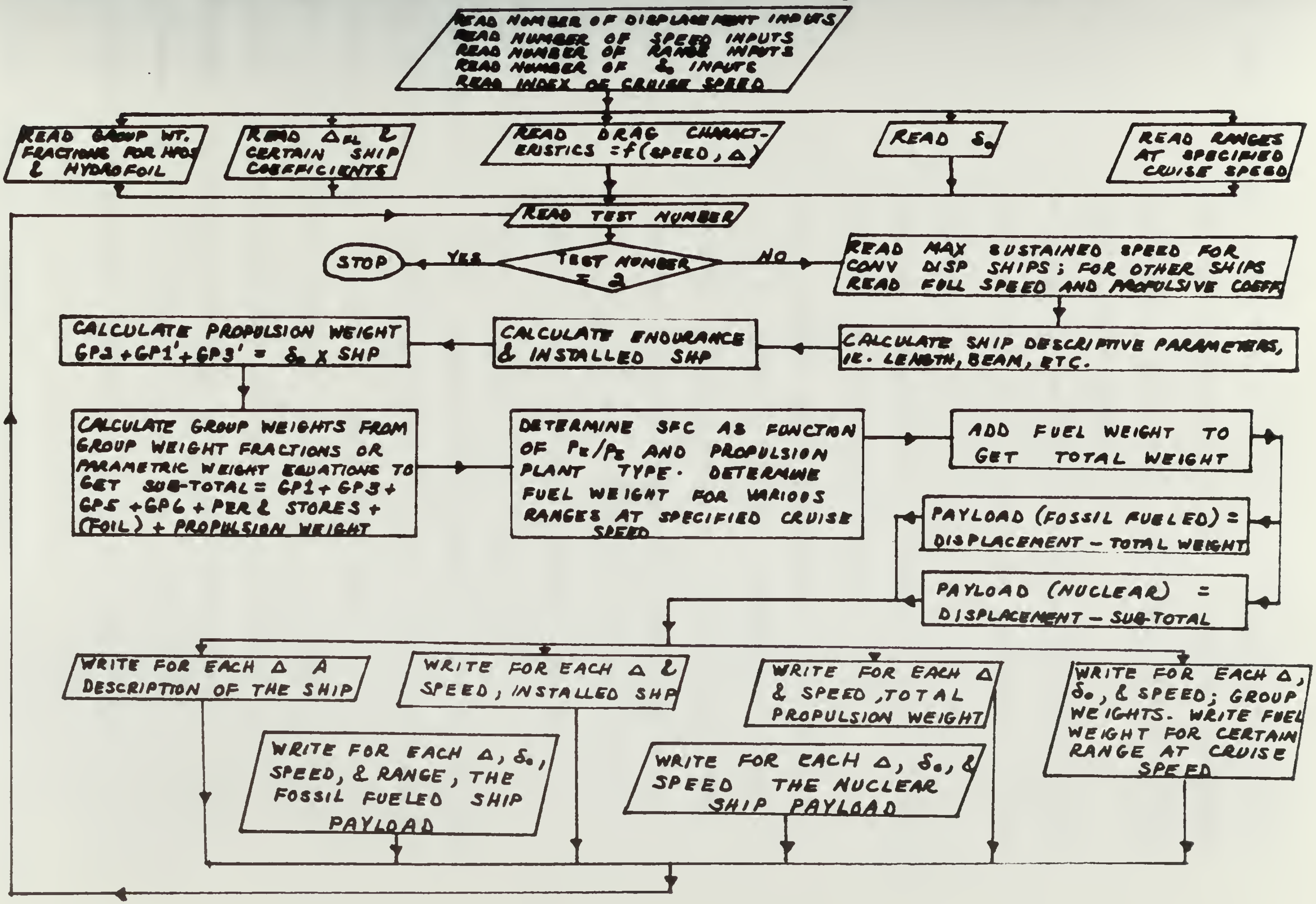
1. Overall specific propulsion weight, δ.
2. Speed (maximum sustained speed for conventional displacement speed and full speed for high performance ships
3. Displacement
4. Zero and 12% weight fraction payloads

Although this chapter will only go into a general description of the computer weight models utilized, and present the major results, Appendix B explains in detail each model and provides a further explanation for the major results. Appendix D contains the actual computer listing for each weight model.

3.1 Method of Analysis

The method chosen for analyzing the effect of propulsion plants on high performance ships was through a sensitivity analysis, i.e. freezing certain ship parameters and varying a single parameter to determine its ship impact. Figure 7 shows a general flow chart for these various

FIGURE 7 General Description of Ship Weight Models



sensitivity analyses. As input to the models the following was necessary:

1. Full load displacement in tons and certain descriptive coefficients such as block coefficient, length-to-beam ratio, cushion density, etc.
2. For all except the conventional displacement ship, drag characteristics of the ships as a function of speed and displacement. (Conventional displacement ship installed power was determined from a statistical study of existing ships so that SHP = f(displacement, $V/\sqrt{L}$)
3. Overall specific propulsion weights in lbm/SHP = δ_o = Group 2 Weight/SHP + Group 1' Weight/SHP + Group 3' Weight/SHP (The primes go to zero for fossil-fueled ships since they are weight differences between two similar ships -- one fossil-fueled and one nuclear)
4. Ranges in nautical miles at specific cruise speed
5. Indices to estimate other weight groups

At this point, for the conventional displacement ship, the maximum <u>sustained</u> speeds to be investigated were read in. Before World War II, the ship requirements for speed of a naval ship referred to the speed that the ship could demonstrate on trials over a measured mile. After World War II, however, operators insisted upon a "sustained speed" requirement envisioned as the speed a ship could make using the maximum continuous power of its engines, allowing for a fouled bottom representing the average fouling of one to two years out of dry dock in head seas just short of the severity that would cause the operator to reduce power. Statistical analysis produced a judgment that the combined effect of fouling

and head seas would increase the average SHP required to maintain a given speed by 25.%. Therefore, the criteria was to calculate the speed versus SHP curve for smooth water and clear bottom and simply reading the sustained speed on that curve at the 80% full power point.

Unfortunately, for the high performance ships, since there are only interim procedures (L1) in light of the lack of true statistical data on rough water drag reduction, the hydrofoil full speed was based on calm water drag profiles with a correction factor of +10.% hullborne and a +7.5% foilborne. For the high performance displacement ship, the correction factor +23.75% was made, and for the SES a correction factor of 20.%. Therefore, the old "sustained speed" or the "full speed" of the high performance ships are similar in concept. The full speeds and corresponsing drags of the high performance ships were thus introduced.

It also became necessary for the high performance ship to use for each speed a propulsive coefficient for a waterjet propulsion system or for a supercavitating propeller to anticipate the possible use of either.

Following these inputs, the ship parameters were calculated as was the endurance and installed shaft horsepower. Then the specific propulsion weights were multiplied by the installed shaft horsepower to determine the propulsion weight.

$$\text{Group 2 Weight} + \text{Group 1' Weight} + \text{Group 3' Weight} = \delta_o \text{ X SHP} = \text{Propulsion Weight} \tag{3.1}$$

After this was completed, group weight fractions or parametric weight equations were utilized to determine the other weight groups excluding Group 4 and 7. Adding these weight groups and the propulsion weight yielded the sub-total:

Sub-total = Group 1 Weight + Group 3 Weight + Group 5 Weight + Group 6 Weight + Personnel & Stores Weight + Propulsion Weight (3.2)

The burnable fuel required for ranges at a specified cruise speed was then determined depending on the assumed plant type (gas turbine, steam, medium speed diesel, low speed diesel) and the ratio of endurance power to installed power (See Appendix B for details of specific fuel consumption models). Fuel weight was then added to the sub-total weight to get a total weight.

Therefore, the payloads became:

Payload Weight (Fossil-fueled) = Full Load Displacement - Total Weight (3.3)

Payload Weight (Nuclear) = Full Load Displacement - Sub-Total Weight (3.4)

This output data was then further broken down as outlined in the following sections to reveal the effects of the propulsion plant on the ship.

3.2 Conventional Displacement Ship Analysis

3.2.1 Description of Model

The conventional displacement ship was analyzed through use of the Mandel weight model (M5). In this particular model the parametric weight equations, endurance and installed shaft horsepower were based upon a statistical study of a large number of existing conventional displacement ships built before 1970. The following were specific inputs:

1. Full load displacements (tons) --- 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, 10,000
2. Overall specific propulsion weight (lbm/SHP) --- 5, 10, 20, 30, 50, 100, 120
3. Range at 20 knots (nm) --- 1000, 2000, 3000, 4000, 6000, 8000, 10,000
4. Max sustained speed (knots) --- 25, 28, 30, 35, 40

The specific ships analyzed are described in Table 5.

3.2.2 Payload vs Speed for Varying Specific Propulsion Weights

As shown in Figures 8 and 10, gas turbine plants with $\delta_o = 10.0$ lbm/SHP would vastly improve speed and/or payload weights as opposed to installed steam plants with $\delta_o = 20.0$ lbm/SHP. For instance, a gas turbine plant with $\delta_o = 10.0$ lbm/SHP could for a ship displacement (Δ will denote displacement) of 10,000 tons and range of 8000 nm (20 knots cruise speed) provide a 12% weight fraction payload at about 40 knots maximum sustained speed. For a similar ship displacement, a steam plant with $\delta_o = 20.0$ lbm/SHP would for a 8000 nm range and 12% weight fraction payload, allow 35 knots. It should be noted that current gas turbine propelled conventional ships such as FFG-7 and DD-963 have $\delta_o = 14.4$ lbm/SHP and 15.1 lbm/SHP, respectively. Present steam plants such as installed in FF-1052 and CG-16 have $\delta_o = 26.7$ lbm/SHP and 24.6 lbm/SHP respectively.

Figures 8 through 10 morever demonstrate that for conventional fossil-fueled ships, since current U. S. naval commitments dictate trans-oceanic ranges, only by reducing δ_o through use of gas turbines, will speeds and/or payload weight fractions be increased. The impact of δ_o can be even

TABLE 5

CONVENTIONAL DISPLACEMENT SHIP PRINCIPAL DIMENSIONS AND COEFFICIENTS

FULL LOAD DISPL (TONS)	1000	6000	2000	7000	3000	8000	4000	9000	5000	10,000
PRISMATIC COEFF	.600	.600	.600	.600	.600	.600	.600	.600	.600	.600
VOLUMETRIC COEFF	.00196	.00196	.00196	.00196	.00196	.00196	.00196	.00196	.00196	.00196
BEAM/DRAFT RATIO	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75
LENGTH/BEAM RATIO	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
BEAM	27.5	50.0	34.7	52.6	39.7	55.0	43.7	57.2	47.0	59.3
LENGTH	261.4	474.9	329.3	500.0	377.0	522.7	414.9	543.7	446.9	563.1
DRAFT	10.0	18.2	12.6	19.1	14.4	20.0	15.9	20.8	17.1	21.6

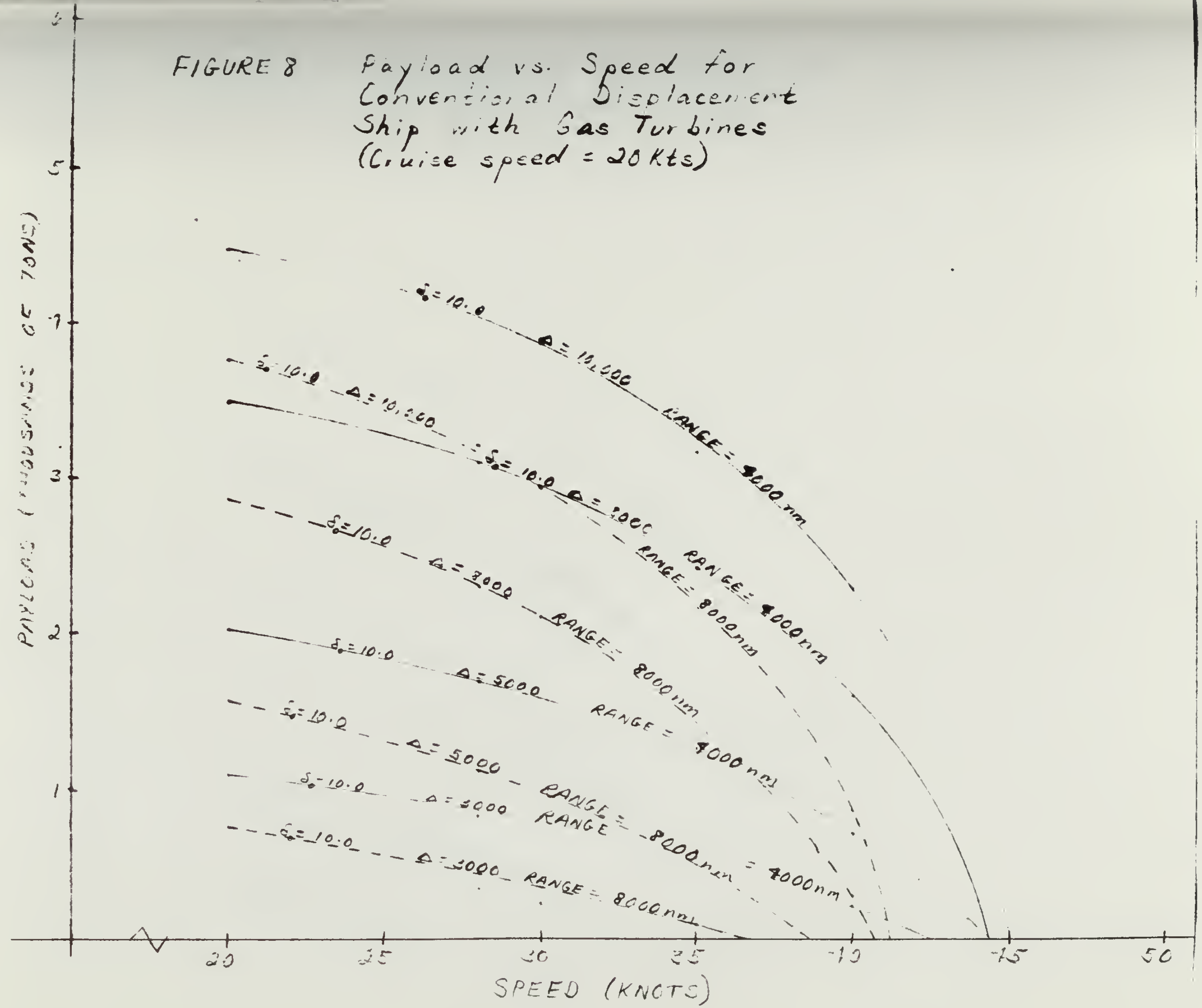


FIGURE 8 Payload vs. Speed for Conventional Displacement Ship with Gas Turbines (Cruise speed = 20 Kts)

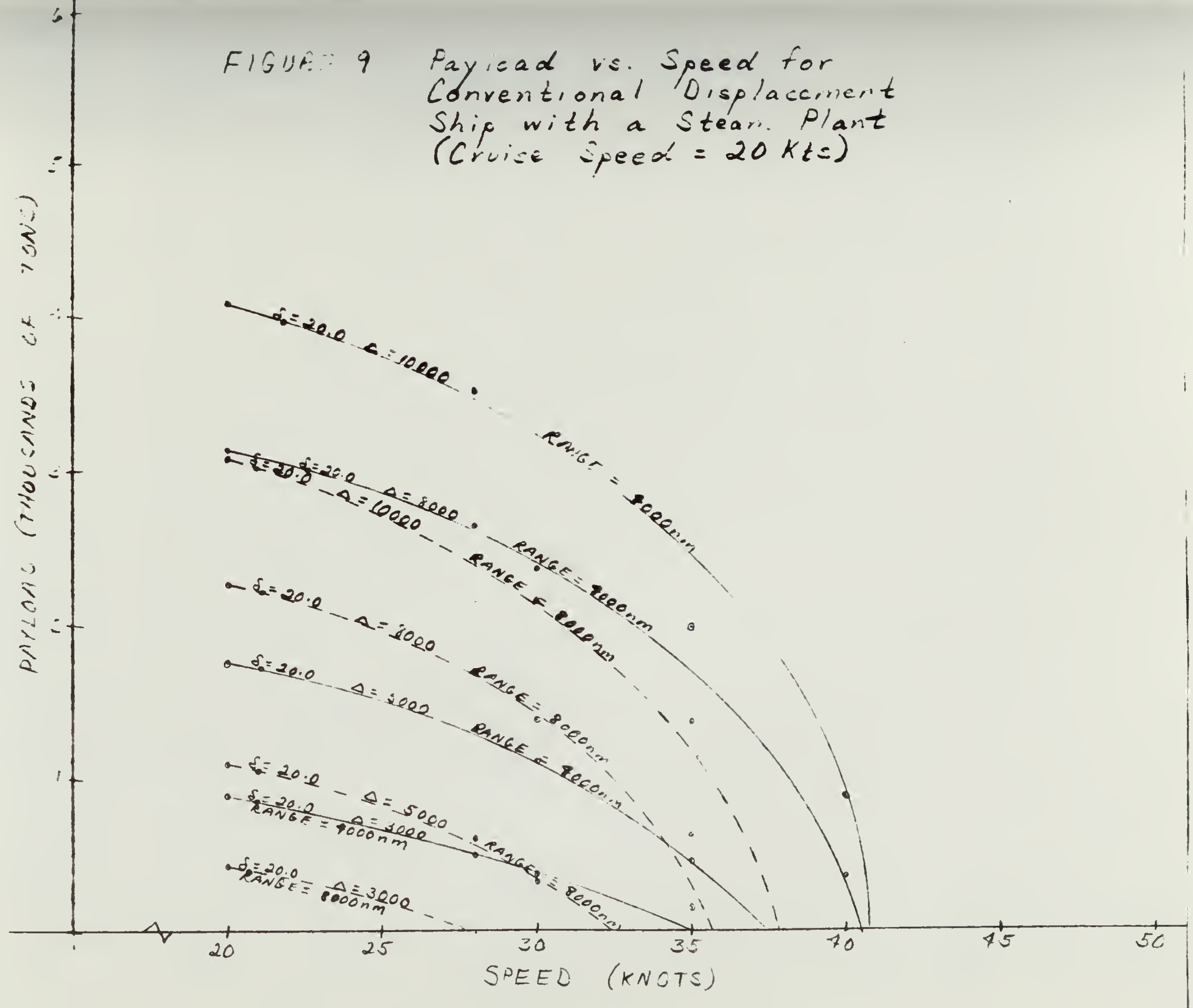
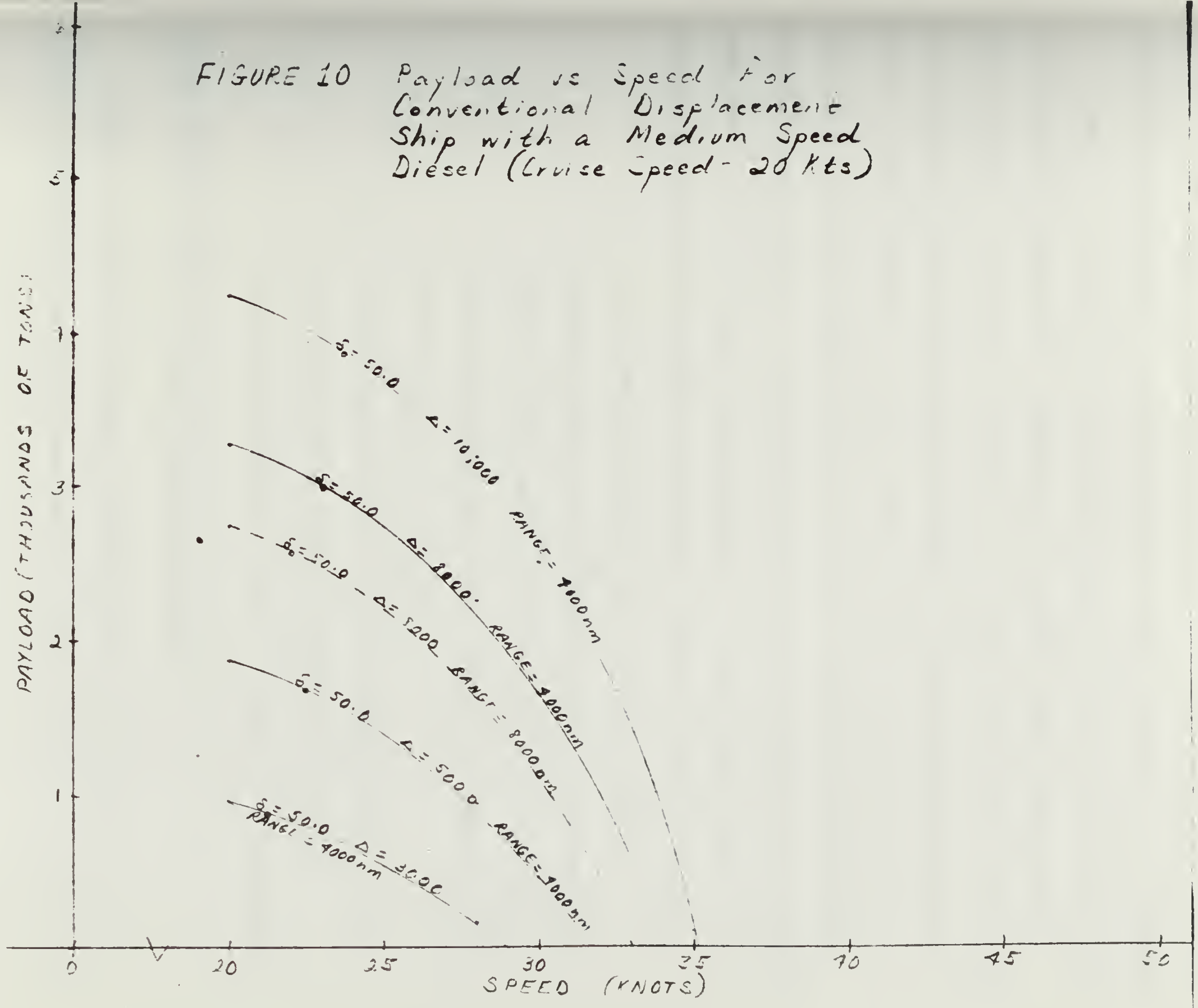


FIGURE 9 Payload vs. Speed for Conventional Displacement Ship with a Steam Plant (Cruise Speed = 20 Kts)

FIGURE 10 Payload vs Speed For Conventional Displacement Ship with a Medium Speed Diesel (Cruise Speed - 20 Kts)



more emphatically seen in Figure 10 for a medium speed diesel with δ_o = 50.0 lbm/SHP. Even though the medium speed diesel offers the best fuel economy, the much greater overall specific propulsion weight negates the fuel savings.

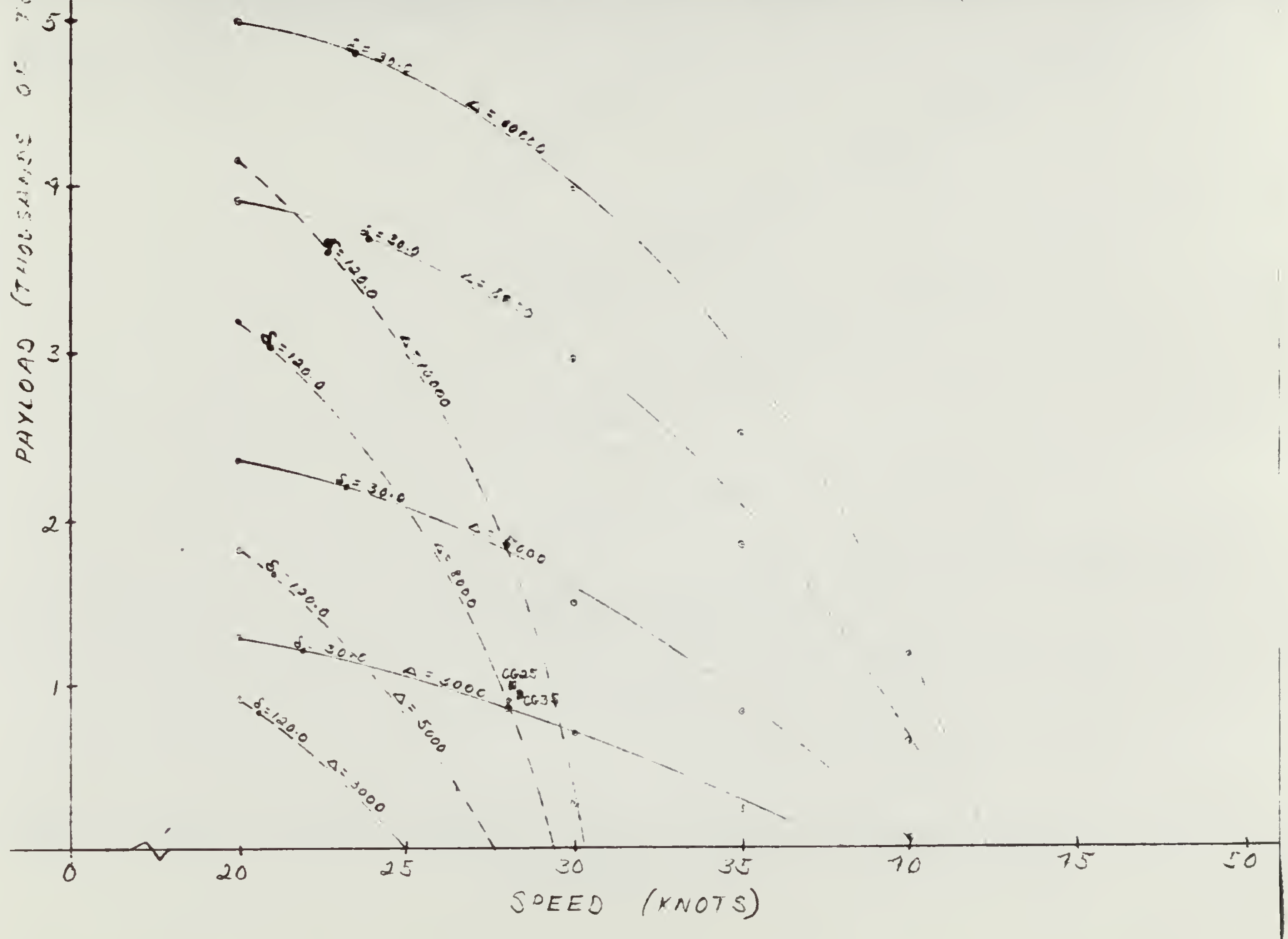
However, if a nuclear plant is substituted for the fossil-fueled plant, the fuel may be essentially traded in for a higher weight nuclear plant. Unfortunately, as was shown in Section 2.4.2, the current naval pressurized water reactor δ_o is limited to 120.0 lbm/SHP. As can be seen in Figure 11, for δ_o = 120.0 lbm.SHP, the naval pressurized water reactor can only be installed on cruisers above 8500 tons and still provide 28 knots maximum sustained speed and 10 - 12% weight fraction payloads required by operational commanders. If the nuclear plant specific propulsion weight could be reduced to about 30.0 lbm/SHP, the following options would materalize:

1. Current nuclear cruisers could increase maximum sustained speed to about 39 knots for 12% payload, or increase payload weight fraction to 37% and maintain maximum sustained speed at 28 knots, or increase payload to 23% and speed to 35 knots.
2. Destroyer escorts with full load displacement of 3000 tons could acquire nuclear endurance at 34 knots maximum sustained speed and 12% weight fraction payloads.

3.2.3 Nuclear Weight Domains For Ship Installation

Figure 12 shows for a nuclear propulsion plant the required δ_o for various conventional ship displacements and maximum sustained speeds. The

FIGURE 11 Payload vs Speed for Conventional Displacement Ship with Nuclear Propulsion



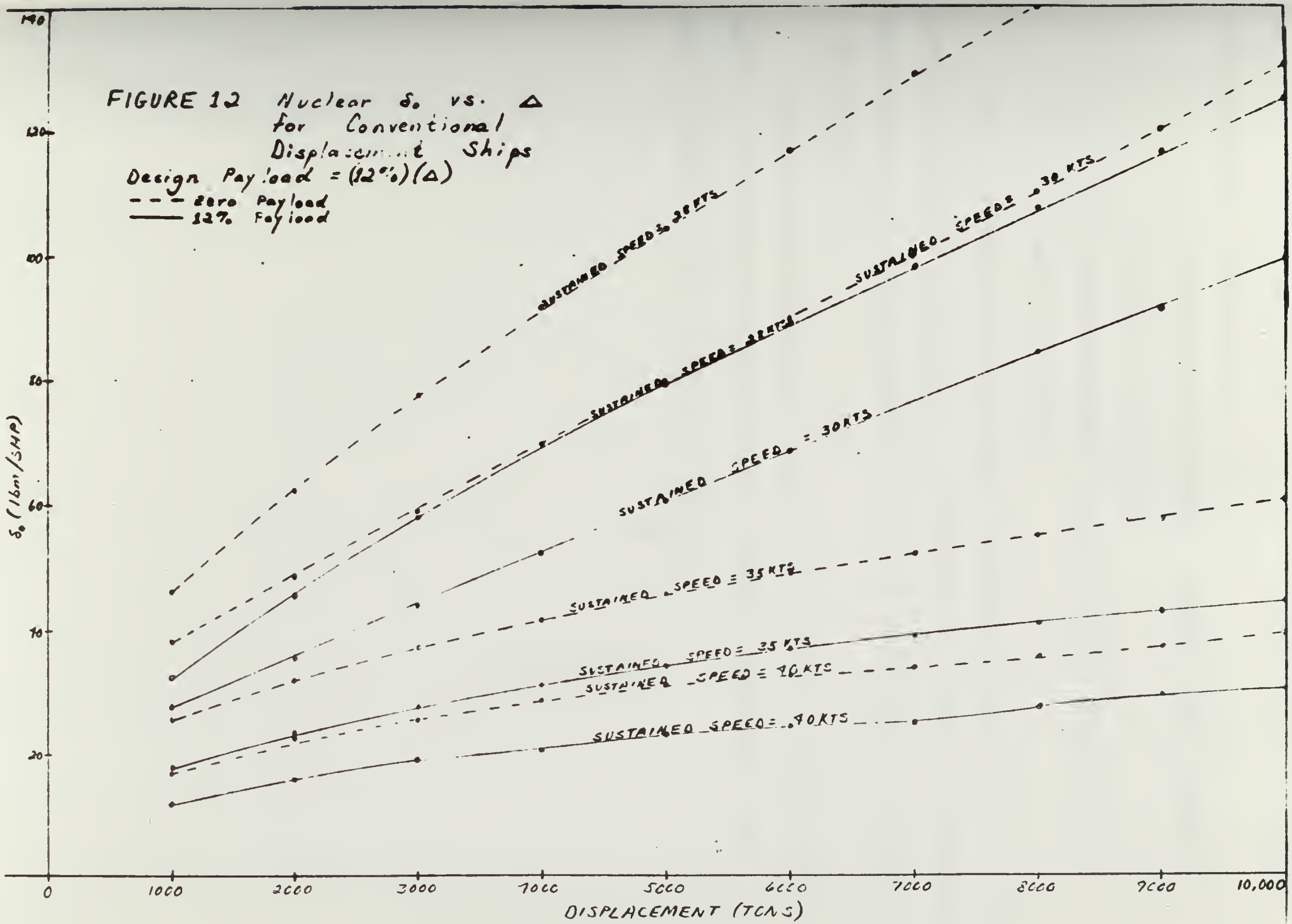


FIGURE 12 Nuclear δ_o vs. Δ for Conventional Displacement Ships

dotted lines indicate zero payload and the solid lines indicate 12% weight fraction payload. Two conclusions can be seen:

1. As displacement increases, a larger weight propulsion plant can be accomodated.
2. As speed decreases, a larger weight propulsion plant can be accomodated.

Figure 13 shows the complete story. Present pressurized water reactor plants of 60,000 SHP require about 120 lbm/SHP such as CGN-25. This limits speed and size to a maximum sustained speed of 28 knots and 8500 tons with a 12% payload.

To gain nuclear endurance on smaller conventional displacement ships and/or increase maximum sustained speed, the nuclear propulsion limit must be reduced. Table 6 summarizes results.

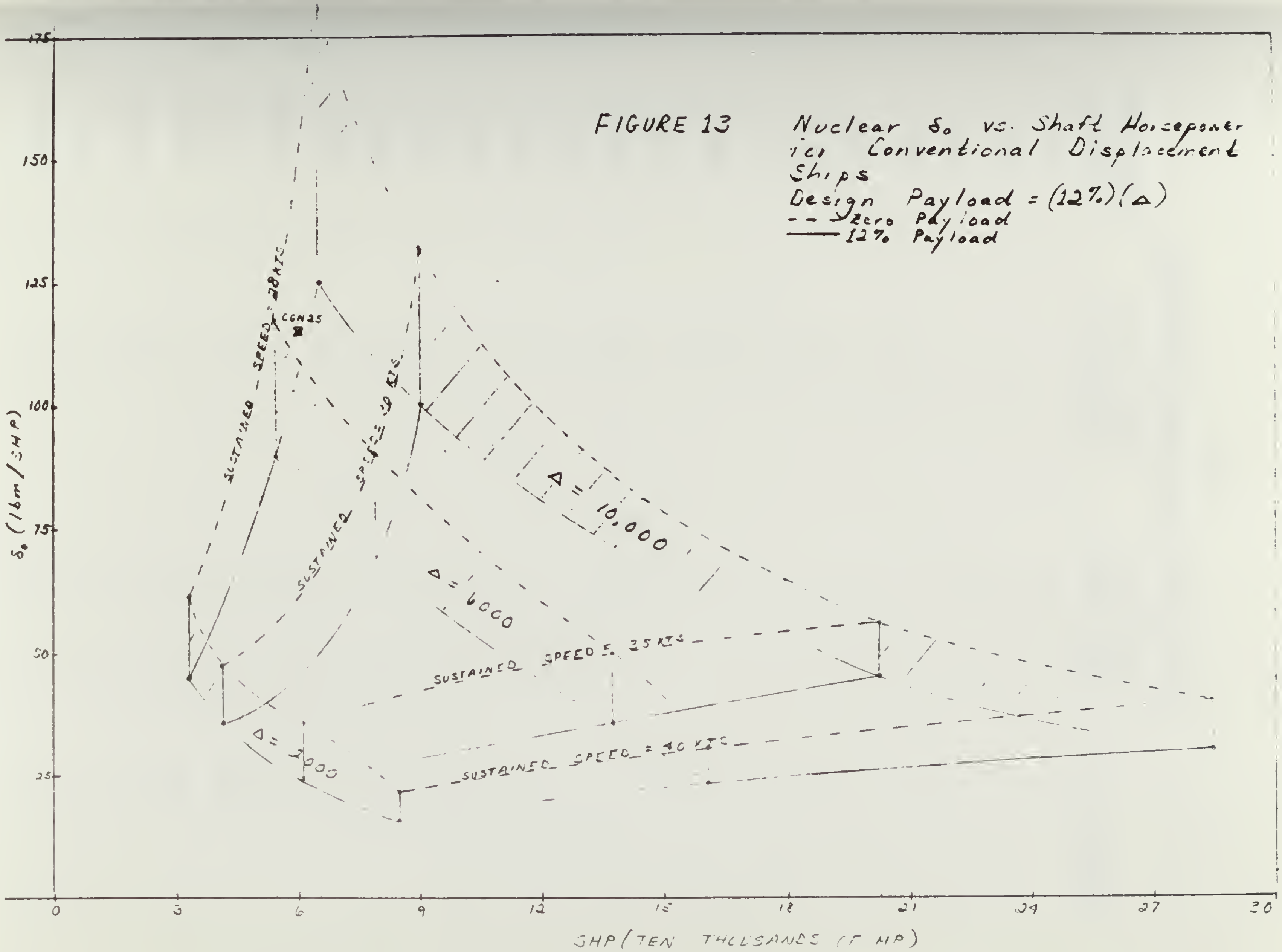


FIGURE 13
Nuclear δo vs. Shaft Horsepower for Conventional Displacement Ships
Design Payload = (12%)(Δ)
-- Zero Payload
— 12% Payload
CGN25
SUSTAINED SPEED = 28KTS
SUSTAINED SPEED = 30 KTS
SUSTAINED SPEED = 35 KTS
SUSTAINED SPEED = 40 KTS
Δ = 10,000
Δ = 6000
Δ = 2000
δo (lbm/SHP)
175
150
125
100
75
50
25
0
3
6
9
12
15
18
21
24
27
30
SHP (TEN THOUSANDS OF HP)

TABLE 6

CONVENTIONAL DISPLACEMENT SHIP δ_e LIMITS

DISPLACEMENT (TONS)	PAYLOAD WEIGHT FRACTION %	MAX SUSTAINED SPEED (KTS)	δ_e (lbm/SHP)
2,000	0	28	62
2,000	12	28	45
2,000	0	30	48
2,000	12	30	36
2,000	0	35	36
2,000	12	35	24
2,000	0	40	22
2,000	12	40	16
6,000	0	28	117
6,000	12	28	90
6,000	0	30	90
6,000	12	30	69
6,000	0	35	50
6,000	12	35	35
6,000	0	40	30
6,000	12	40	24
10,000	0	28	185
10,000	12	28	128
10,000	0	30	132
10,000	12	30	100
10,000	0	35	60
10,000	12	35	45

TABLE 6 continued

DISPLACEMENT (TONS)	PAYLOAD WEIGHT FRACTION %	MAX SUSTAINED SPEED (KTS)	δ_e(lbm/SHP)
10,000	0	40	40
10,000	12	40	30

3.3 High Performance Ship Analysis

3.3.1 Description of Model

The high performance ship was analyzed through the use of a hypothetical displacement ship based on the HOC (Hydrofoil Ocean Combatant) design criteria (See Appendix B 2.2 for HOC design criteria) as applied to a Series 64 Model 4803 hull. The following were specific inputs:

1. Full load displacement (tons) -- 1000, 2000, 3000, 4000
2. Specific propulsion weight (lbm/SHP) -- 5, 10, 20, 30, 50, 100, 120
3. Range at 20 knots (nm) -- 1000, 2000, 3000, 4000, 5000, 6000
4. Full speed (knots) -- 20, 30, 40, 50, 60

The specific ships analyzed are described in Table 7.

3.3.2 Payload vs Speed for Varying Specific Propulsion Weights

Comparing Figure 14 to Figure 8 reveals that utilizing high performance design criteria as embodied in the hydrofoil is one method in which speed and/or payload may be increased for a given displacement and overall specific propulsion weight. This was shown in more detail in (G2). Going to a nuclear plant, high performance criteria would allow the nuclear δ_o to increase 120 to 400% and still provide the same payload and speed that a much lower δ_o for a conventional displacement ship would have been able to provide (See Figure 15). For instance for Δ = 4000, sustained speed = 33 knots, payload = 1650 tons; the HPDS required δ_o = 50.0 lbm/SHP; whereas the conventional displacement δ_o = 15.0 lbm/SHP. The effects of high performance design criteria on allowable δ_o is summarized in Table 8.

TABLE 7

PRINCIPAL DIMENSIONS & COEFFICIENTS -- HPDS

FULL LOAD DISP (TONS)	1000	2000	3000	4000
BLOCK COEFF	0.450	0.450	0.450	0.450
MAX SECT AREA COEFF	0.714	0.714	0.714	0.714
DISPL/LENGTH RATIO	32.5	32.5	32.5	32.5
BEAM/DRAFT RATIO	4.0	4.0	4.0	4.0
LENGTH/BEAM RATIO	9.948	9.948	9.948	9.948
BEAM (FT)	31.5	39.7	45.4	50.0
LENGTH (FT)	313.4	394.9	452.0	497.5
DRAFT (FT)	7.9	9.9	11.4	12.5
$S/(\Delta \cdot L)^{1/2}$	16.561	16.561	16.561	16.561
$S\ (FT^2)$	9271.	14,717.	19,285	23,362.

FIGURE 14 Payload vs. Speed for High Performance Displacement Ship with Gas Turbines and Supercavitating Propellers (Cruise Speed = 20 Kts)

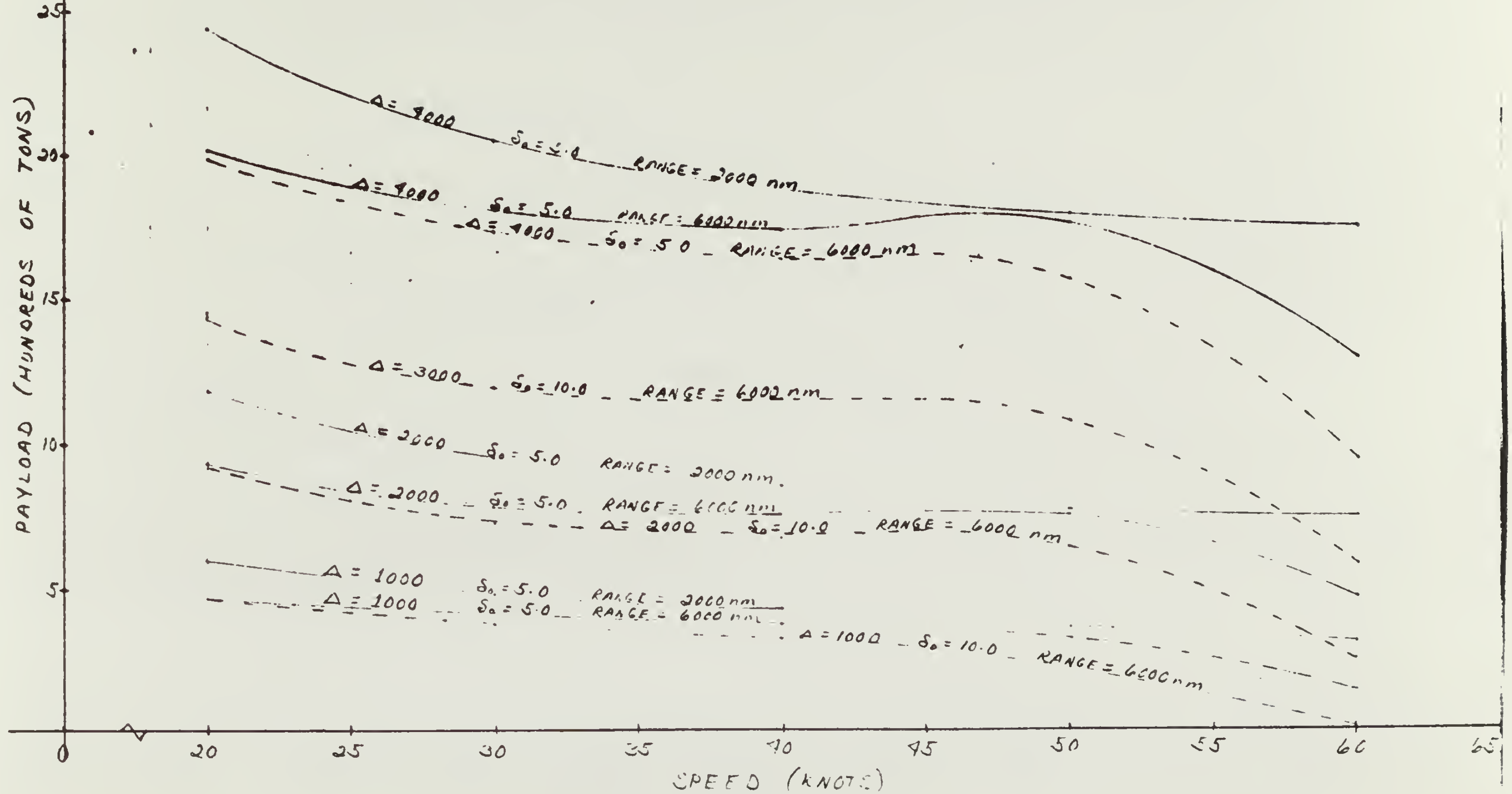


FIGURE 15 Payload vs Speed for High Performance Displacement Ship with Nuclear Propulsion and Supercavitating Propellers

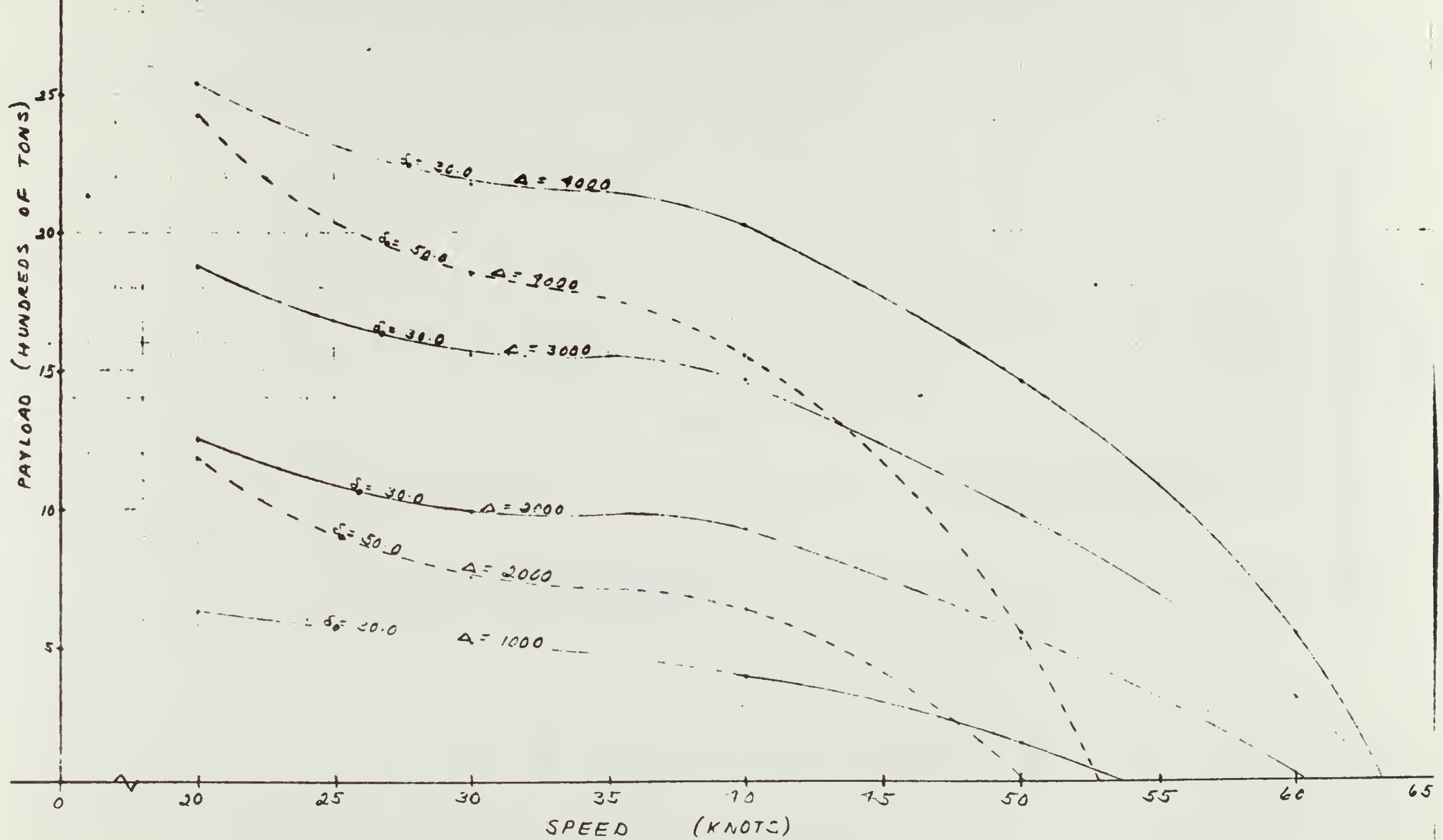


TABLE 8

HPDS & CONVENTIONAL SHIP COMPARISION

DISPLACEMENT (TONS)	PAYLOAD WEIGHT FRACTION	MAX SPEED (KTS)	CONV δ_o	HPDS δ_o	$\frac{\delta_{o\ HPDS}}{\delta_{o\ CONV}}$
1,000	0	30	38	116	3.05
1,000	12	30	28	96	3.43
1,000	0	40	17	73	4.29
1,000	12	40	12	60	5.00
2,000	0	30	48	114	2.38
2,000	12	30	36	93	2.58
2,000	0	40	22	94	4.27
2,000	12	40	16	76	4.75
3,000	0	30	59	130	2.20
3,000	12	30	44	108	2.45
3,000	0	40	26	110	4.23
3,000	12	40	19	90	4.74
4,000	0	30	60	160	2.67
4,000	12	30	52	131	2.52
4,000	0	40	29	120	4.14
4,000	12	40	21	98	4.67

3.3.3 Nuclear Weight Domains for Ship Installation

For supercavitating propellers and for waterjet propulsion systems the required nuclear δ_o for various displacement and full speeds are plotted in Figures 16 and 17. Except for 30 knots, allowed δ_o goes up as $\triangle$ increases and speed decreases, although at lower levels than for the conventional displacement ship.

For the maximum speed = 30 knots and $\triangle$ = 1000 tons there is a marked increase in allowable δ_o. This is due to the fact that for this particular model there is a marked decrease in required shaft horsepower due to wave cancellation effects. This occurs at about $V/\sqrt{L}$ = 1.69 for this particular model. For a 2000 ton HPDS, the allowable δ_o increases markedly for similar reasons at 33.6 knots; for 3000 tons at 35.9 knots; and for 4000 tons at 37.7 knots.

Figures 18 and 19 summarise the HPDS results, thus illustrating one possible route for putting higher weight nuclear propulsion plants on smaller displacement ships --- go to hydrofoil design criteria. However, this only suggests a possibility since the marriage of aluminum foundations and concentrated reactor pressure vessel point loads might produce a "structural nightmare." Furthermore, hydrofoil standards reduce R/M/A (reliability, maintainability, and availability) which is most certainly not compatible with the design philosophy of nuclear propulsion plants. It does, however, suggest the effects of design criteria. Final results are summarized in Table 9.

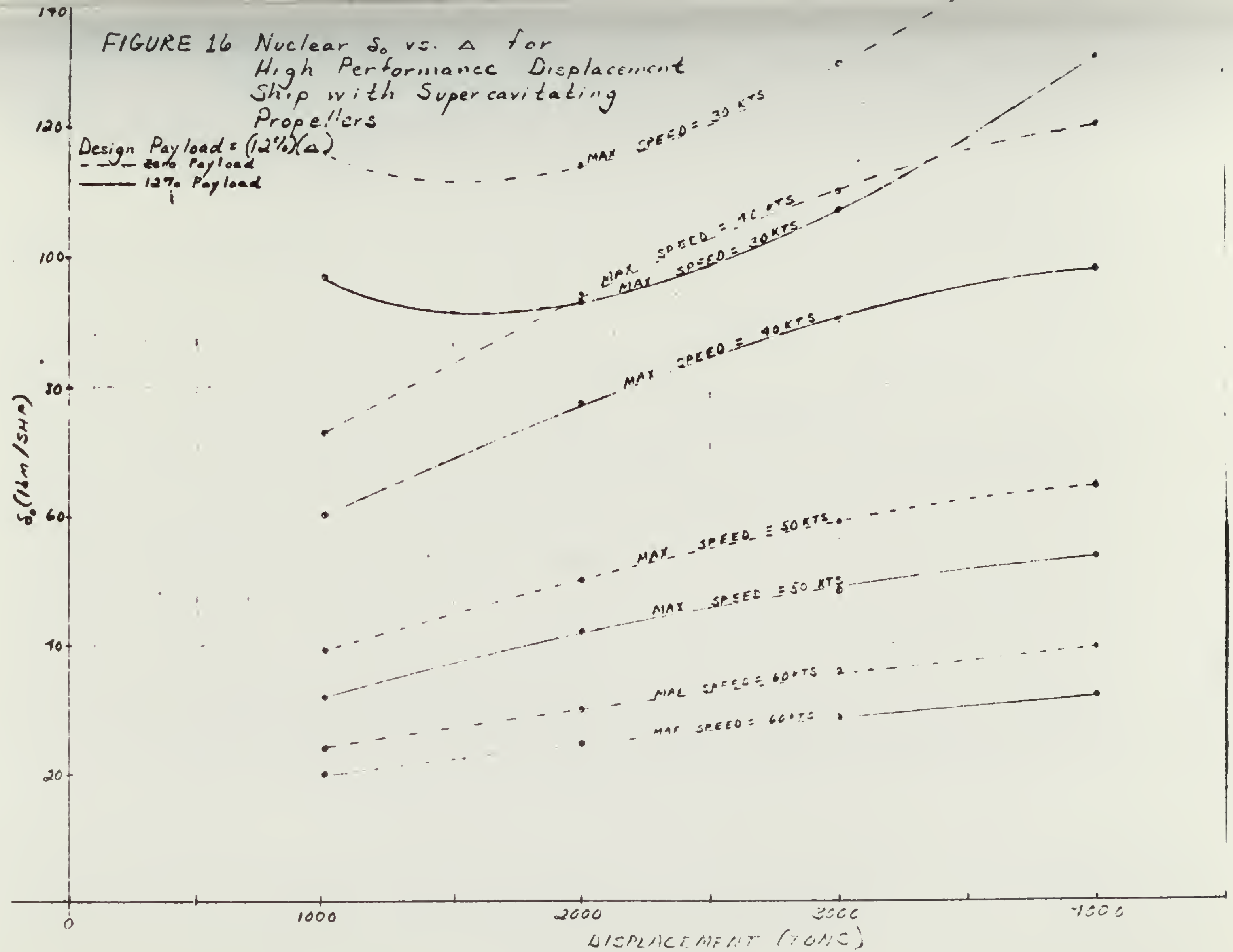


FIGURE 16 Nuclear S_o vs. Δ for High Performance Displacement Ship with Supercavitating Propellers

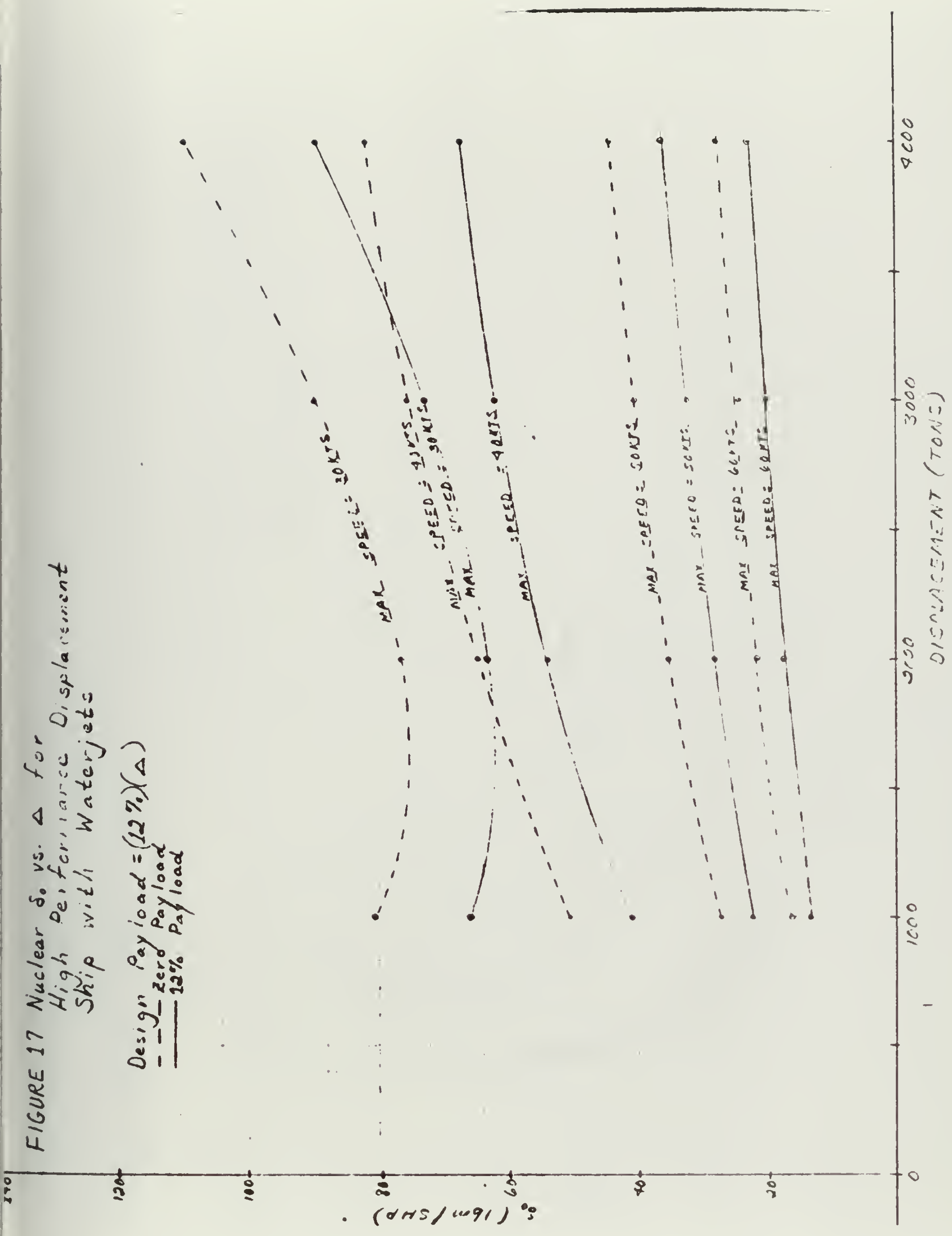


FIGURE 17 Nuclear δo vs. Δ for High Performance Displacement Ship with Waterjets

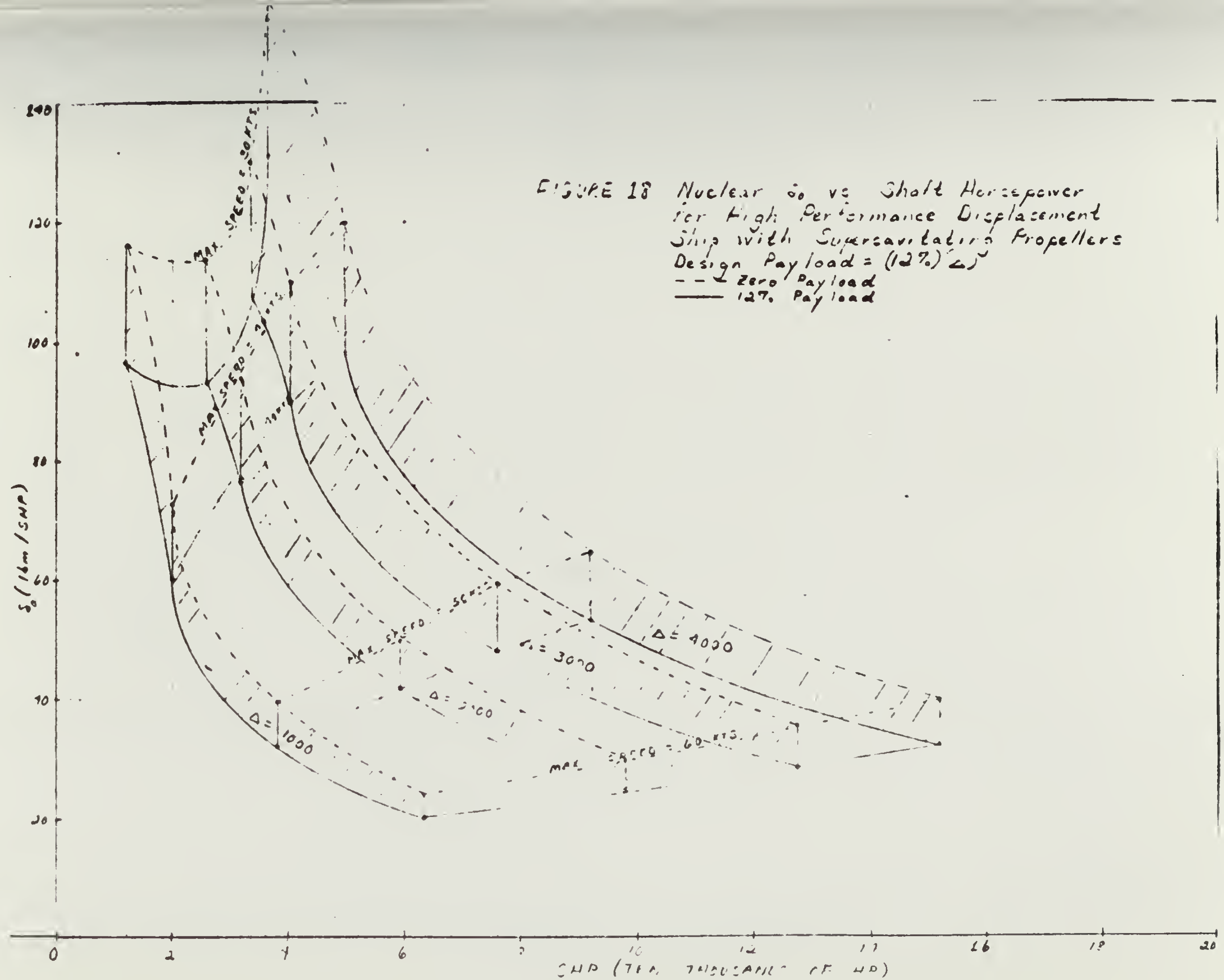


FIGURE 18 Nuclear S_0 vs Shaft Horsepower for High Performance Displacement Ship with Supercavitating Propellers Design Payload = (12%) Δ

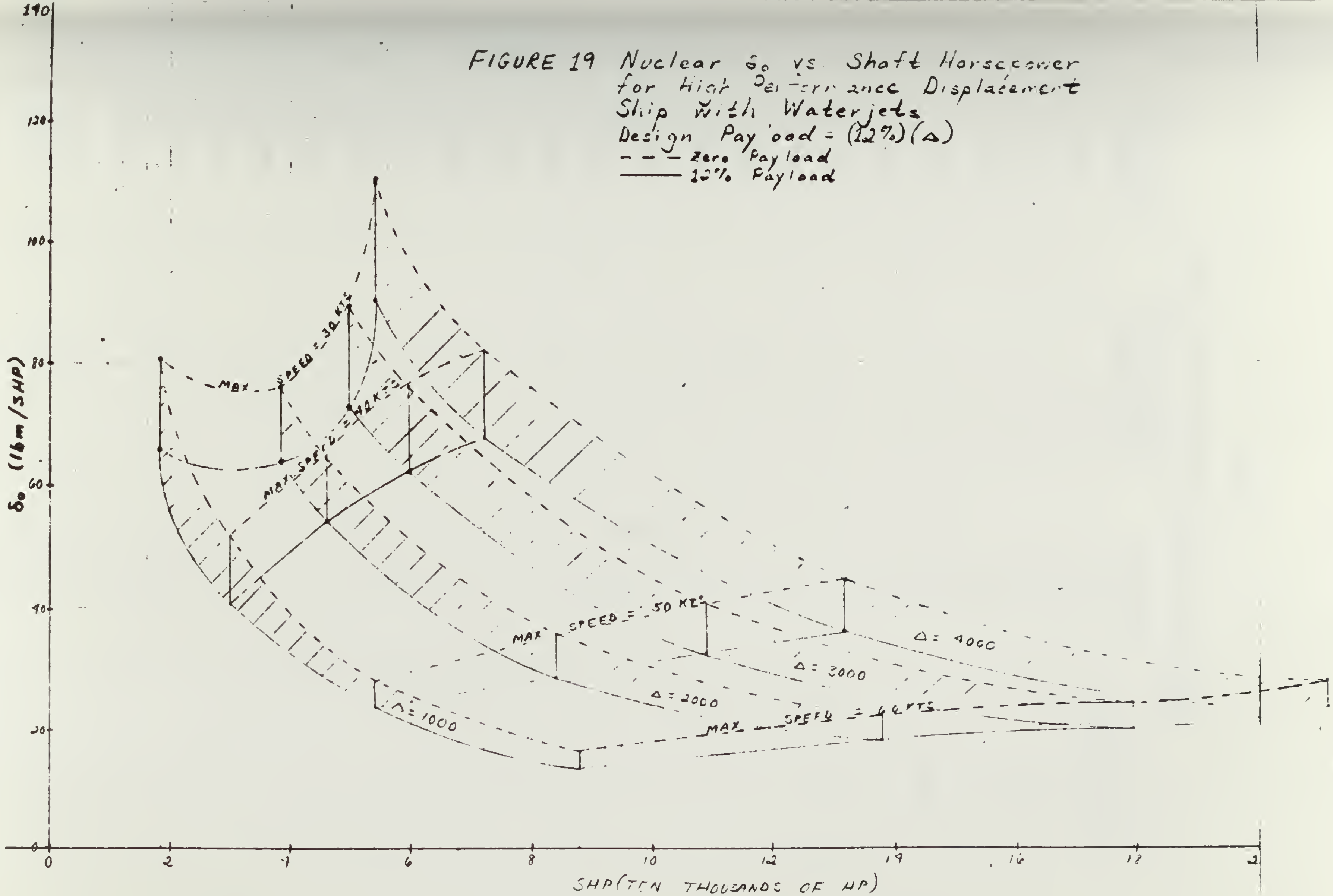


FIGURE 19 Nuclear δ_o vs Shaft Horsepower for High Performance Displacement Ship with Waterjets

TABLE 9

HPDS δ LIMITS (SUPERCAVITATING PROPELLER)

DISPLACEMENT (TONS)	PAYLOAD WEIGHT FRACTION (%)	MAX SPEED (KTS)	δ_o(lbm/SHP)
1,000	0	30	116
1,000	12	30	96
1,000	0	40	73
1,000	12	40	60
1,000	0	50	40
1,000	12	50	32
1,000	0	60	24
1,000	12	60	20
2,000	0	30	114
2,000	12	30	93
2,000	0	40	94
2,000	12	40	76
2,000	0	50	50
2,000	12	50	42
2,000	0	60	30
2,000	12	60	24
4,000	0	30	160
4,000	12	30	131
4,000	0	40	120
4,000	12	40	98
4,000	0	50	64
4,000	12	50	53
4,000	0	60	40
4,000	12	60	32

3.4 Hydrofoil Analysis

3.4.1 Description of Model

To analyze the hydrofoil, at the low end of the displacement spectrum the model was based on the 230 ton PHM and at the high end the 1278 ton HOC design. The following were specific inputs:

1. Full load displacement (tons) -- 230, 750, 1278
2. Specific propulsion weight (lbm/SHP) -- 5, 10, 20, 30, 50, 100, 120
3. Range hullborne at 20 knots (nm) -- 1000, 2000, 3000, 4000, 5000, 6000
4. Full speed (kts) -- 20, 25, 30, 35, 40, 45, 50

The specific ships analyzed are described in Table 10.

3.4.2 Payload vs Speed for Varying Specific Propulsion Weights

Figure 20 indicates the range limitations of hydrofoils. For small displacement hydrofoils such as the PHM, range at a hullborne cruise speed of 20 knots is limited to around 1000 nm; ranges necessary for trans-oceanic operation can be achieved only for displacements greater than 1000 tons. (Slightly greater ranges are achieved foilborne just past the "hump" speed). If,however, a nuclear propulsion plant could be designed with $\delta_o = 30.0$ lbm/SHP, hydrofoils could conceivably be designed to accomodate the weight as shown in Figure 21.

3.4.3 Nuclear Weight Domains for Ship Installation

The required nuclear overall specific propulsion weight δ_o for various displacements Δ and full speeds are plotted in Figures 22 and 23 for the

TABLE 10

PRINCIPAL DIMENSIONS AND COEFFICIENTS

	(PHM)	EXTRAPOLATED HYDROFOIL	(HOC)
FULL LOAD DISP (TONS)	230.0	750.0	1278.0
BLOCK COEFFICIENT	0.494	0.412	0.3799
MAX SECT AREA COEFFICIENT	0.650	0.583	0.555
BEAM/DRAFT RATIO	3.320	3.486	3.565
LENGTH/BEAM RATIO	5.630	5.458	5.121
BEAM	21.26	34.4	41.0
LENGTH	119.7	187.7	210.0
DRAFT	6.4	9.9	11.5

FIGURE 20 Payload vs Speed for Hydrofoil with Gas Turbines and Supercavitating Propellers (Cruise Speed = 20 Kts Hullborne)

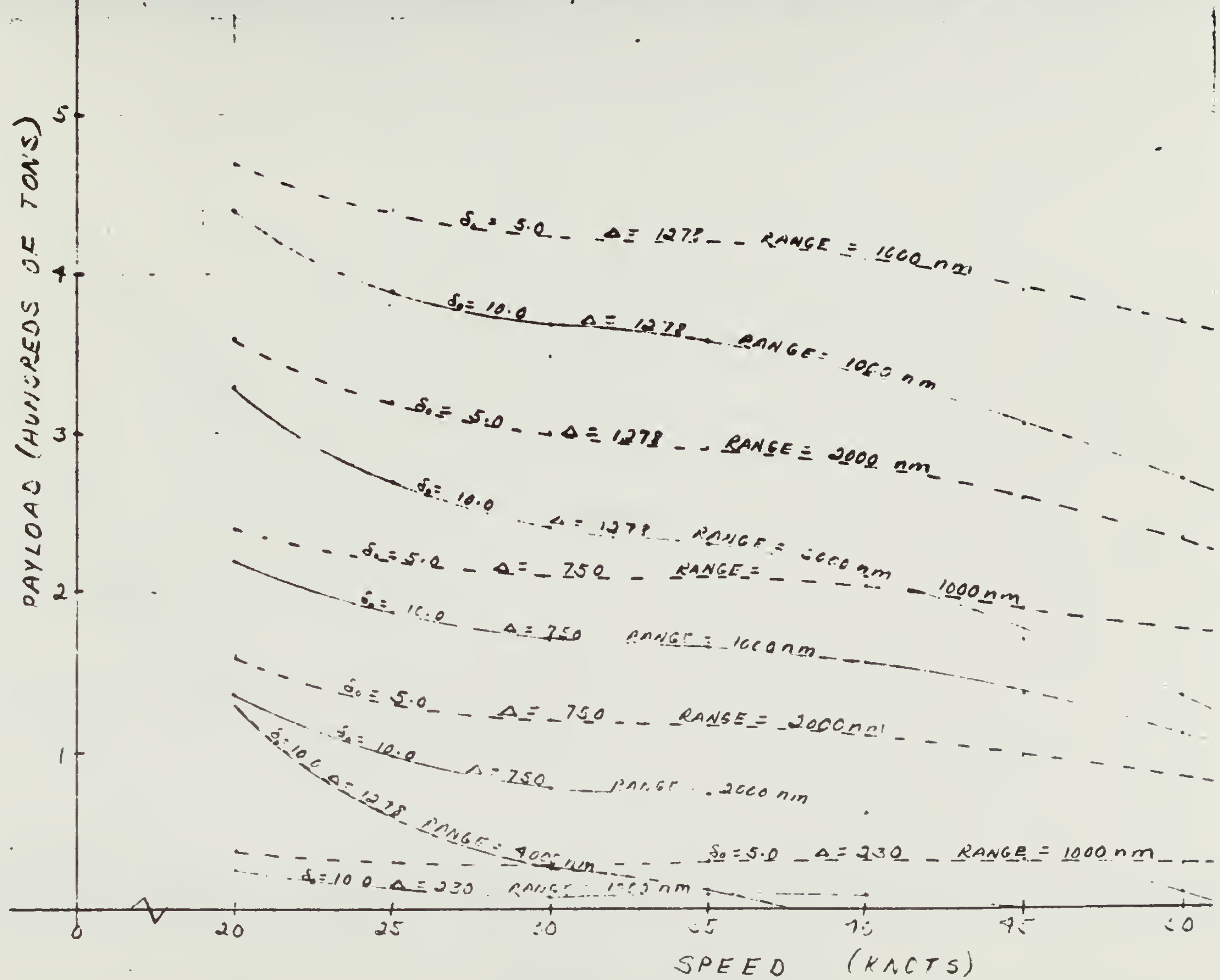


FIGURE 21 · Payload vs. Speed for Hydrofoil with Nuclear Propulsion and Supercavitating Propellers

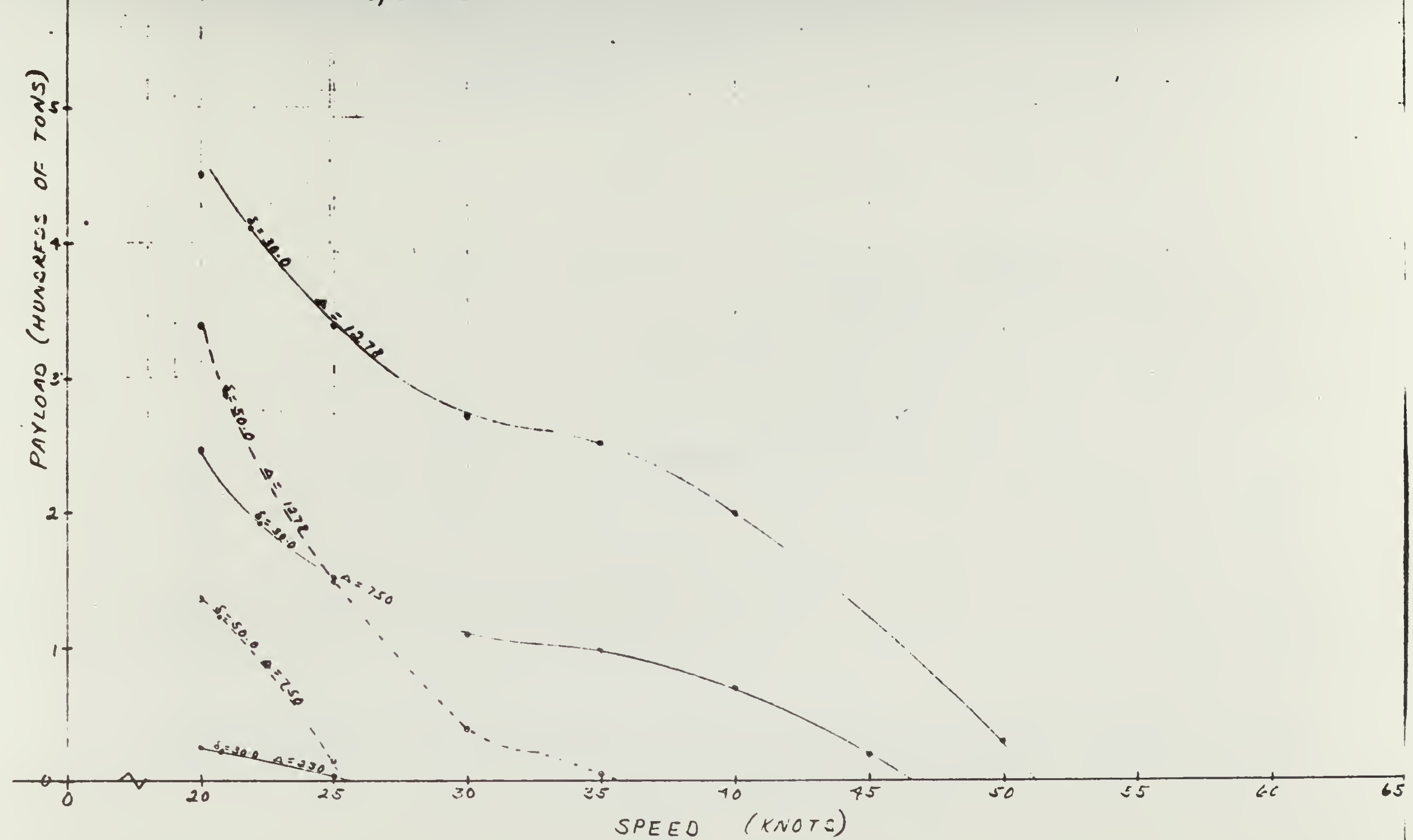
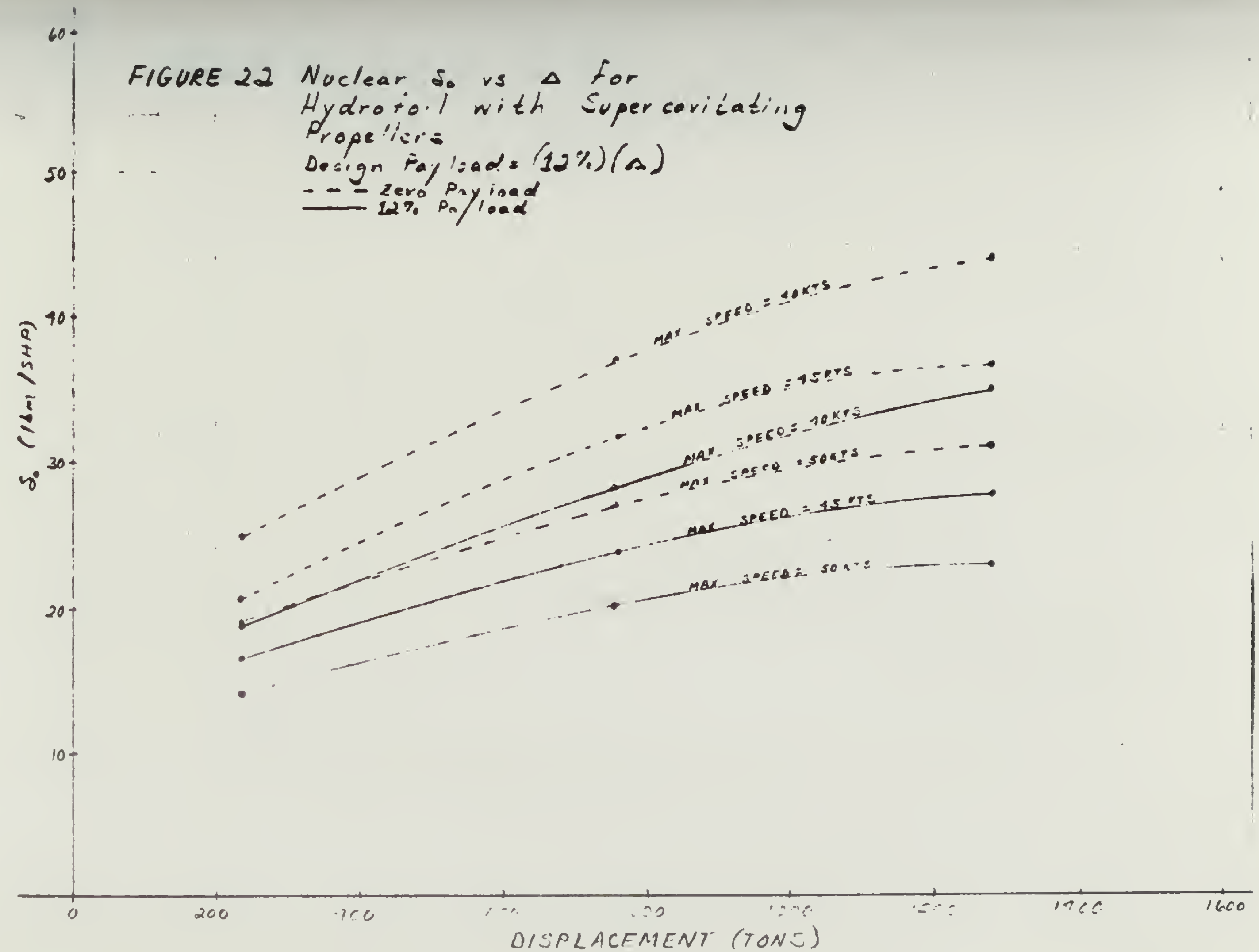


FIGURE 22 Nuclear S_o vs Δ for Hydrofoil with Supercavitating Propellers



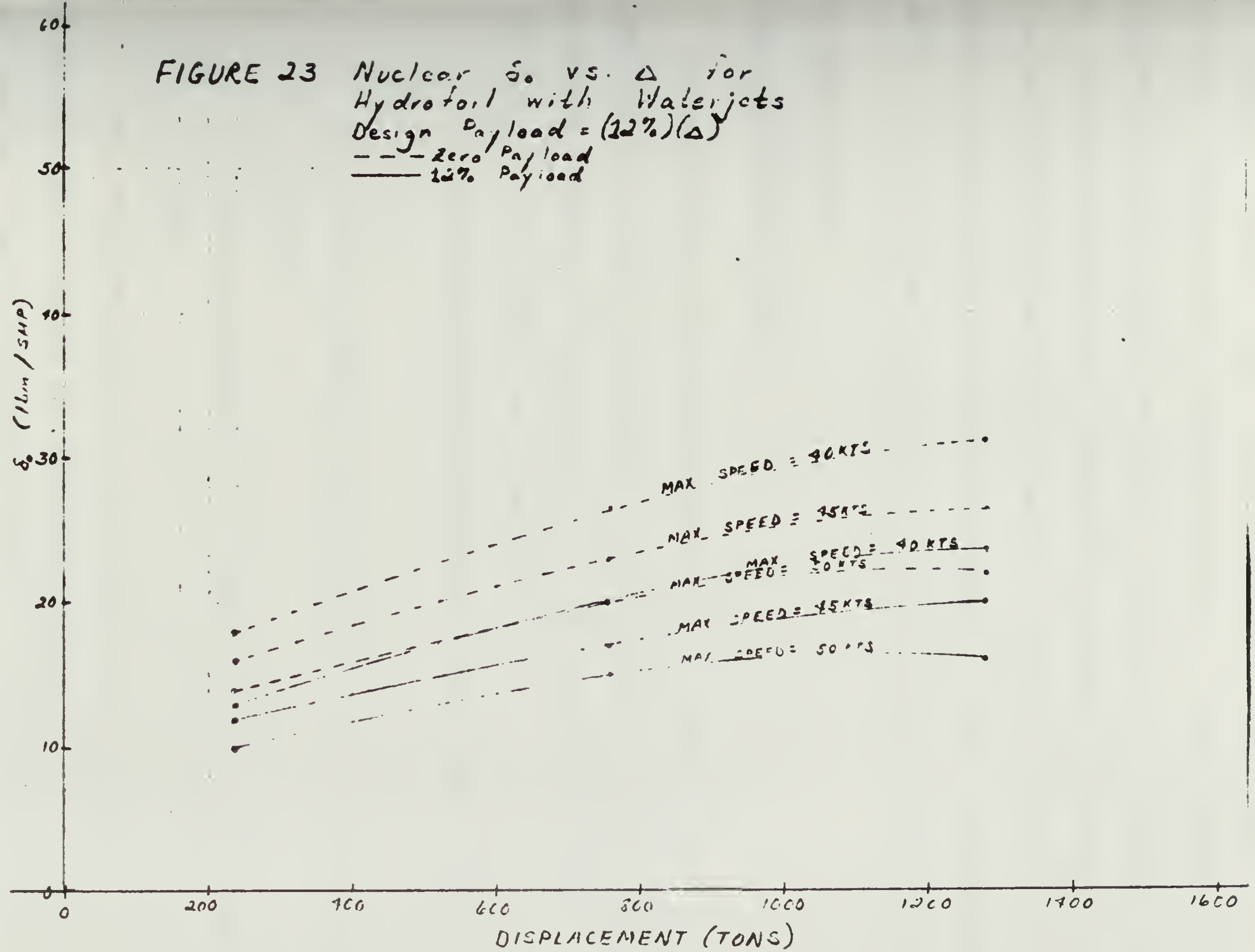


FIGURE 23 Nuclear δ_o vs. Δ for Hydrofoil with Waterjets
Design Payload = (12%)(Δ)
– – – Zero Payload
——— 12% Payload

supercavitating propeller and waterjet propulsion systems. The curves reveal the extremely stringent weight requirements of a hydrofoil. This is further evidenced in Figures 24 and 25 which show that not only are the overall specific propulsion weights low, but the required shaft horsepower are too. This low required δ_o for a low shaft horsepower will be seen later to be especially disadvantageous since most overall specific propulsion weights increase as shaft horsepower decreases. Table 11 summarizes the limits of δ_o for nuclear propulsion plant installation on hydrofoils.

3.5 SES Analysis

3.5.1 Description of Model

The surface effect ship was analyzed through utilization of the Rosenblatt and Sons SES design weight equations and L/D curves. (R10). The cushion pressure to length ratio P_c /L_c , was fixed at 1.5 and l_c /b_c at 2.0 The following were specific inputs:

1. Full load displacements (tons) -- 1000, 2000, 3000, 5000, 10,000
2. Specific propulsion weight (lbm/SHP) -- 5, 10, 20, 30, 50, 100, 120
3. Range at 40 knots (nm) -- 1000, 2000, 3000, 4000, 5000, 6000
4. Full speed (kts) -- 40, 50, 60, 70, 80, 90, 100

The specific ships analyzed are described in Table 12. (Note for Δ = 5000 tons, cushion pressure > 300 lbf/ft^2 which is a technological limit -- leakage becomes too great to maintain the required higher densities.)

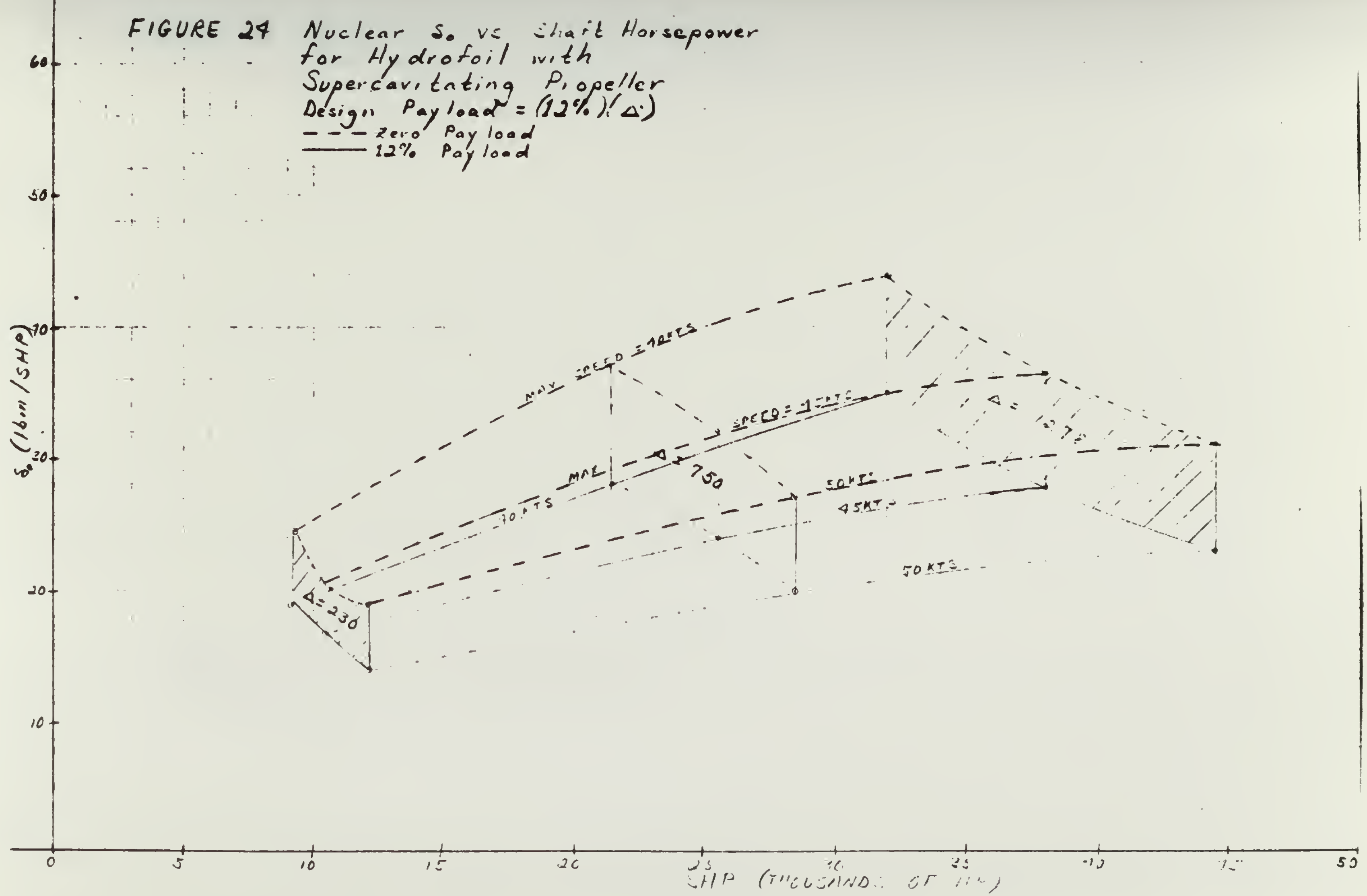


FIGURE 24 Nuclear S_o vs Shaft Horsepower for Hydrofoil with Supercavitating Propeller
Design Payload = (12%)(Δ)

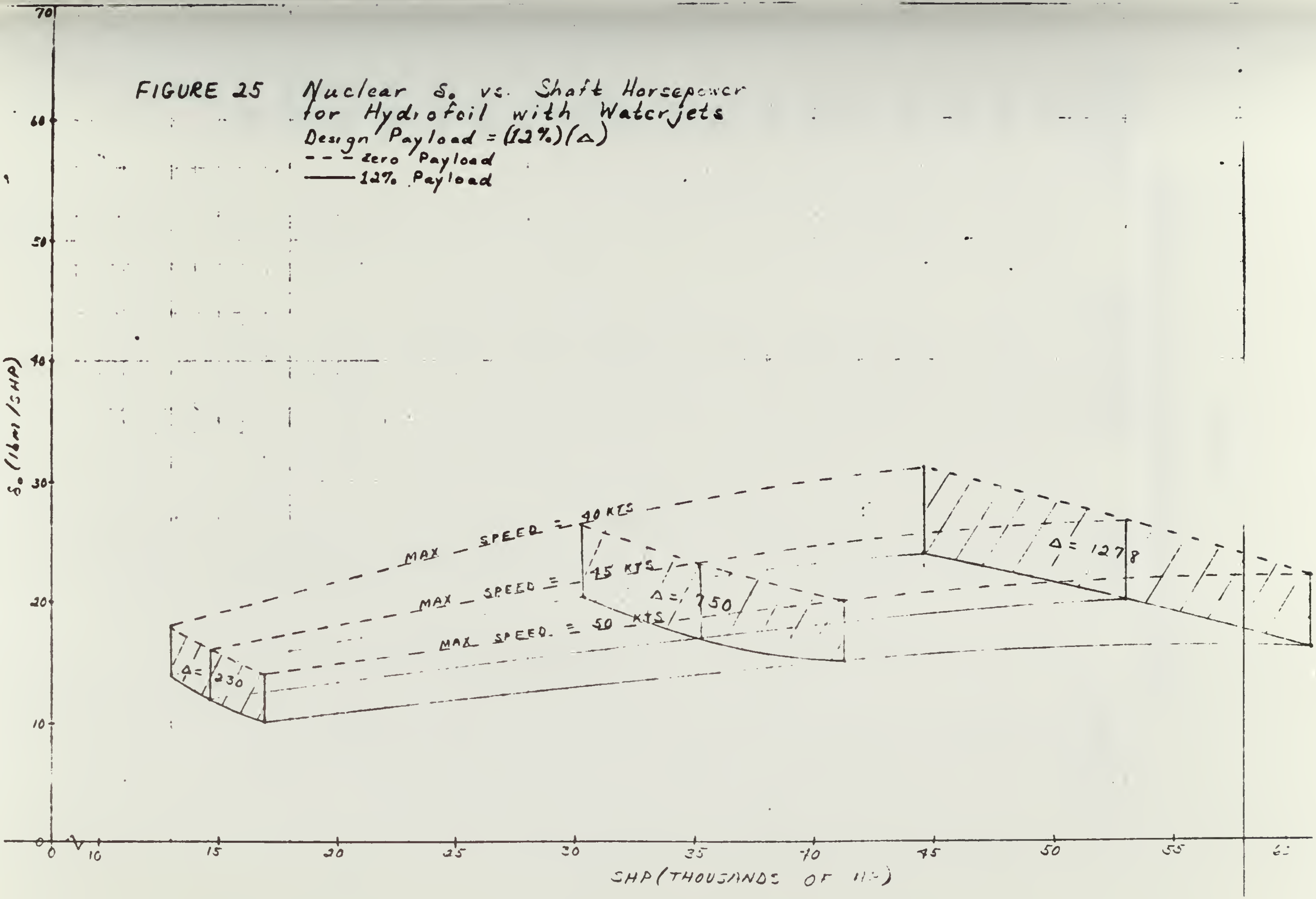


FIGURE 25 Nuclear S_o vs. Shaft Horsepower for Hydrofoil with Waterjets
Design Payload = (12%)(Δ)

TABLE 11

HYDROFOIL δ_e LIMITS (SUPERCAVITATING PROPELLER)

DISPLACEMENT (TONS)	PAYLOAD WEIGHT FRACTION (%)	MAX SPEED (KTS)	δ_e(lbm/SHP)
230	0	40	24
230	12	40	19
230	0	45	20
230	12	45	17
230	0	50	19
230	12	50	14
750	0	40	37
750	12	40	28
750	0	45	32
750	12	45	24
750	0	50	27
750	12	50	20
1,278	0	40	44
1,278	12	40	35
1,278	0	45	36
1,278	12	45	28
1,278	0	50	31
1,278	12	50	23

TABLE 12

PRINCIPAL DIMENSIONS & COEFFICIENTS

FULL LOAD DISP(TONS)	1000	2000	3000	5000	10,000
CUSHION LENGTH	131.4	165.5	189.5	224.7	283.1
CUSHION BEAM	65.7	82.8	94.7	112.3	141.5
CUSHION PRESSURE	197.1	248.3	284.2	337.0	424.6
CUSHION LENGTH/CUSH BEAM	2.0	2.0	2.0	2.0	2.0
CUSH PRESS/CUSH LENGTH	1.5	1.5	1.5	1.5	1.5
BEAM	95.7	112.8	124.7	142.3	171.5
LENGTH	153.4	189.5	215.5	254.7	323.1
CUSHION AREA	8631.1	13701.0	17953.4	25237.4	40061.9
$W/\sqrt{A_c} = \frac{\Delta \cdot 2240}{(\ell_c b_c)^{3/2}}$	2.8	2.8	2.8	2.8	2.8

3.5.2 Payload vs Speed for Varying Specific Propulsion Weights

Although the SES is very much range limited like the hydrofoil, the SES can achieve speeds even up to 100 knots as shown in Figure 26, with comparable hydrofoil weight fraction payloads. The reason the SES can negotiate these speeds, with higher payload weight fractions than the hydrofoil, is attributable to three reasons detailed in Appendix B.

First, the SES does not encounter as great a weight restriction as the hydrofoil. The hydrofoil, it should be noted, pays a heavy weight penalty for the foil system. Although the SES must provide lift fan power, this weight fraction does not increase for higher displacements as quickly as the foil weight increases on the hydrofoil. Secondly, the drag of the low l_c / b_c SES is lower past 45 knots than for the hydrofoil due to the fact that frictional drag, the major part of the drag, is considerably lower due to less wetted surface area. Thirdly, the present size limitations for the hydrofoil limit the hydrofoil to about 1500 - 2000 tons, considerably below the 5000 ton limit for low l_c / b_c SES designs. This size limit further complicates providing weight for fuel on the hydrofoil. As seen in Figure 26, the 5000 ton SES with δ_o= 10.0 lbm/SHP can afford about a 500 ton payload (10%) at 100 knots maximum sustained speed, for a 4000 nm range at a 40 knot cruise speed, quite a carrying improvement over the hydrofoil.

The endurance limitation, as for the hydrofoil, however, still exists for the SES. Examination of Figure 27 reveals that if a nuclear 5000 ton SES with δ_o= 20.0 lb /SHP could be built, a 700 ton payload could be provided, along with nuclear endurance.

FIGURE 26 Payload vs. Speed for Low L_c/L_c SES with Gas Turbines and Supercavitating Propellers
(Cruise Speed = 40 Kts)

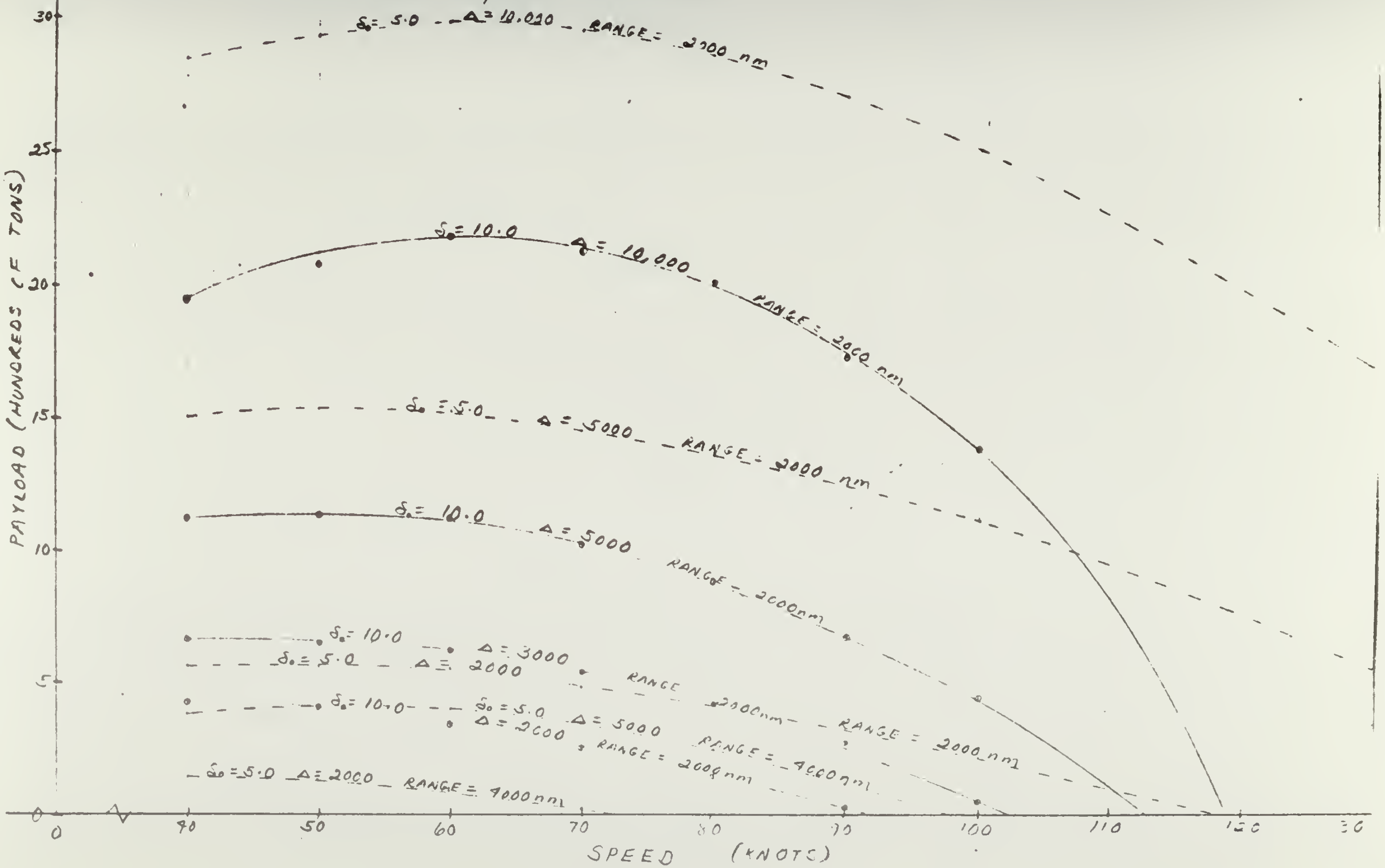
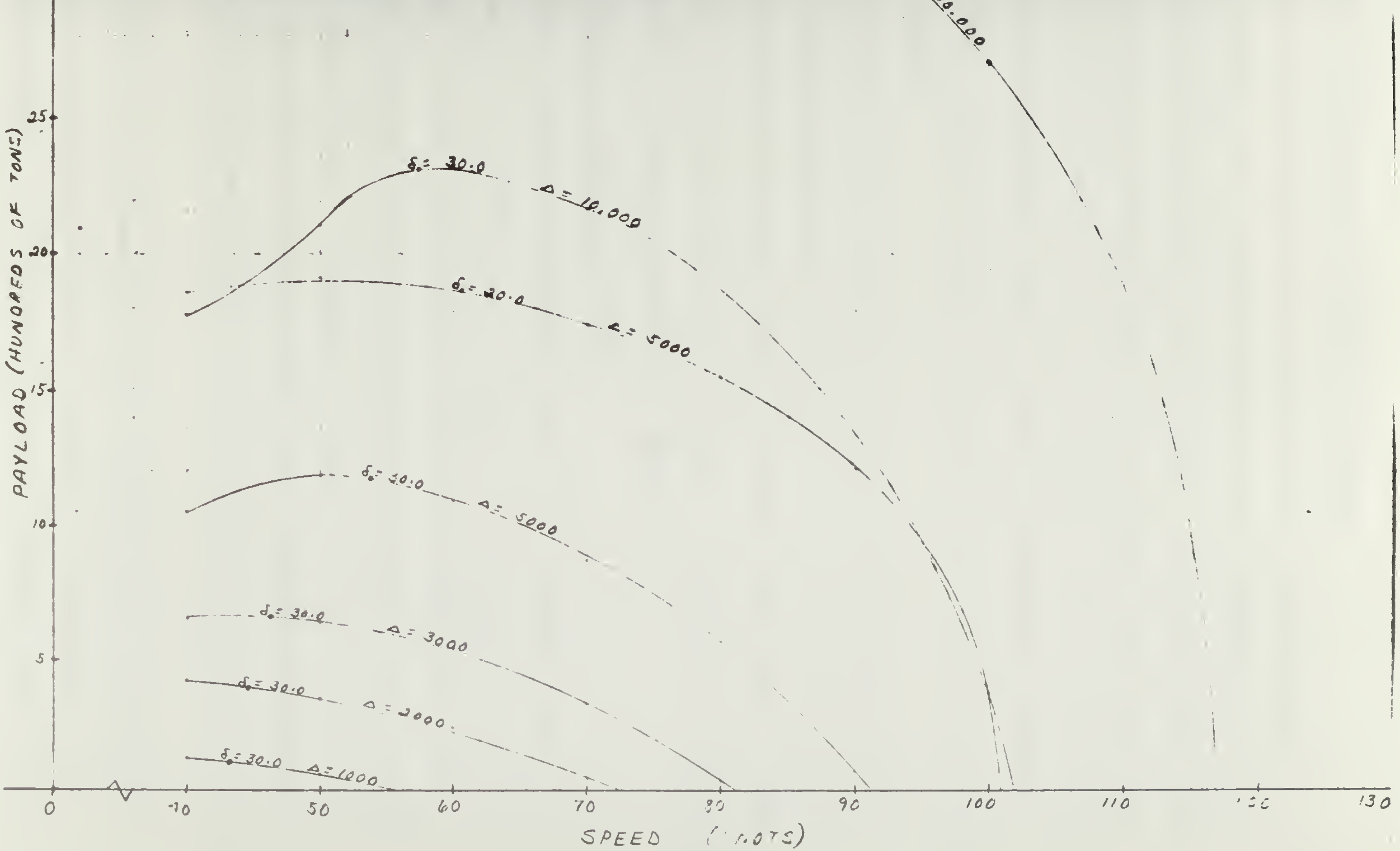


FIGURE 27 Payload vs Speed for Low l_c/b_c SES with Nuclear Propulsion and Supercavitating Propellers



3.5.3 Nuclear Weight Domains for Ship Installation

Figures 28 and 29 summarize the required nuclear overall specific propulsion weight δ_o and the required shaft horsepower (including lift fan power) for various displacements and full speeds. Comparison between these figures for the SES and similar figures for the hydrofoil again reveal the more stringent weight restrictions of the hydrofoil. For a 12% weight fraction payload and 40 knot full speed, a 1000 ton hydrofoil would require a $\delta_o = 18.$ lbm/SHP, whereas a 60 knot, 12% payload, 1000 ton SES would require a $\delta_o = 23.$ lbm/SHP.

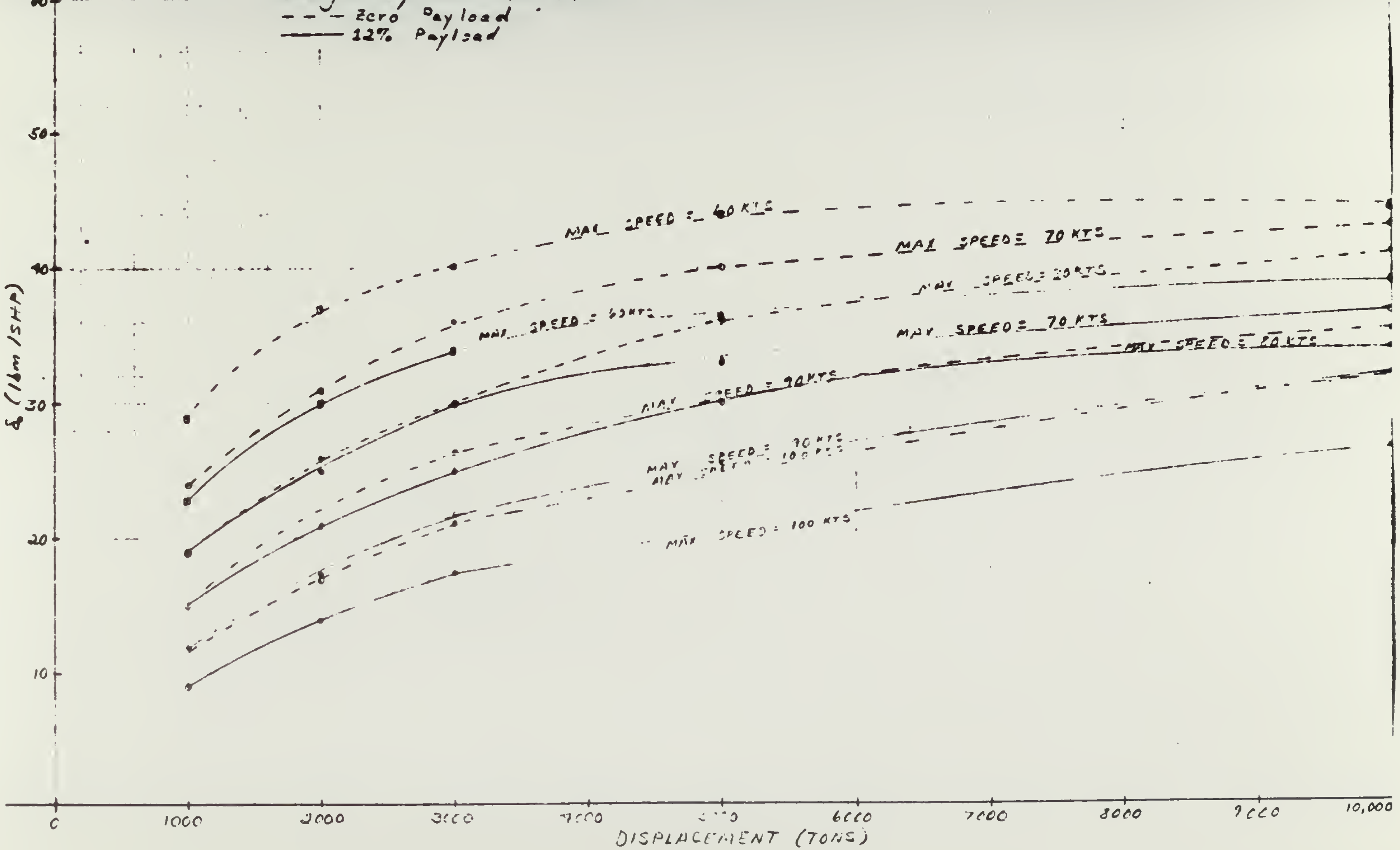
Figures 30 and 31 also reveal that for the higher displacement SES's the shaft horsepower increases to very high levels. This fact may further bracket the feasible SES because as shaft horsepower grows, most certainly the cost will too, until a cost limit is reached. The limits for installing nuclear plants on an SES are summarized in Table 13.

3.6 Limitations of the Computer Models

The models utilized have definite limitations since they are not true synthesis models. All models were weight models so no checks were made with respect to volume and/or stability. The weight models should, however, provide good estimates for the hydrofoil and SES since they are very much weight limited ships. In addition to being weight limited, the high performance ship is also stability limited due to its shallow draft and most conventional displacement ships also simultaneously volume and stability limited.

Most World War II vintage ships were "weight limited" in that heavy projectiles and gun systems controlled the design. With, however, the advent of electronics and increased habitability standards topside, naval

FIGURE 28 Nuclear δ_o vs Δ for Low C_c/b_c SES with Supercavitating Propellers
Design Payload = (12%)(Δ)



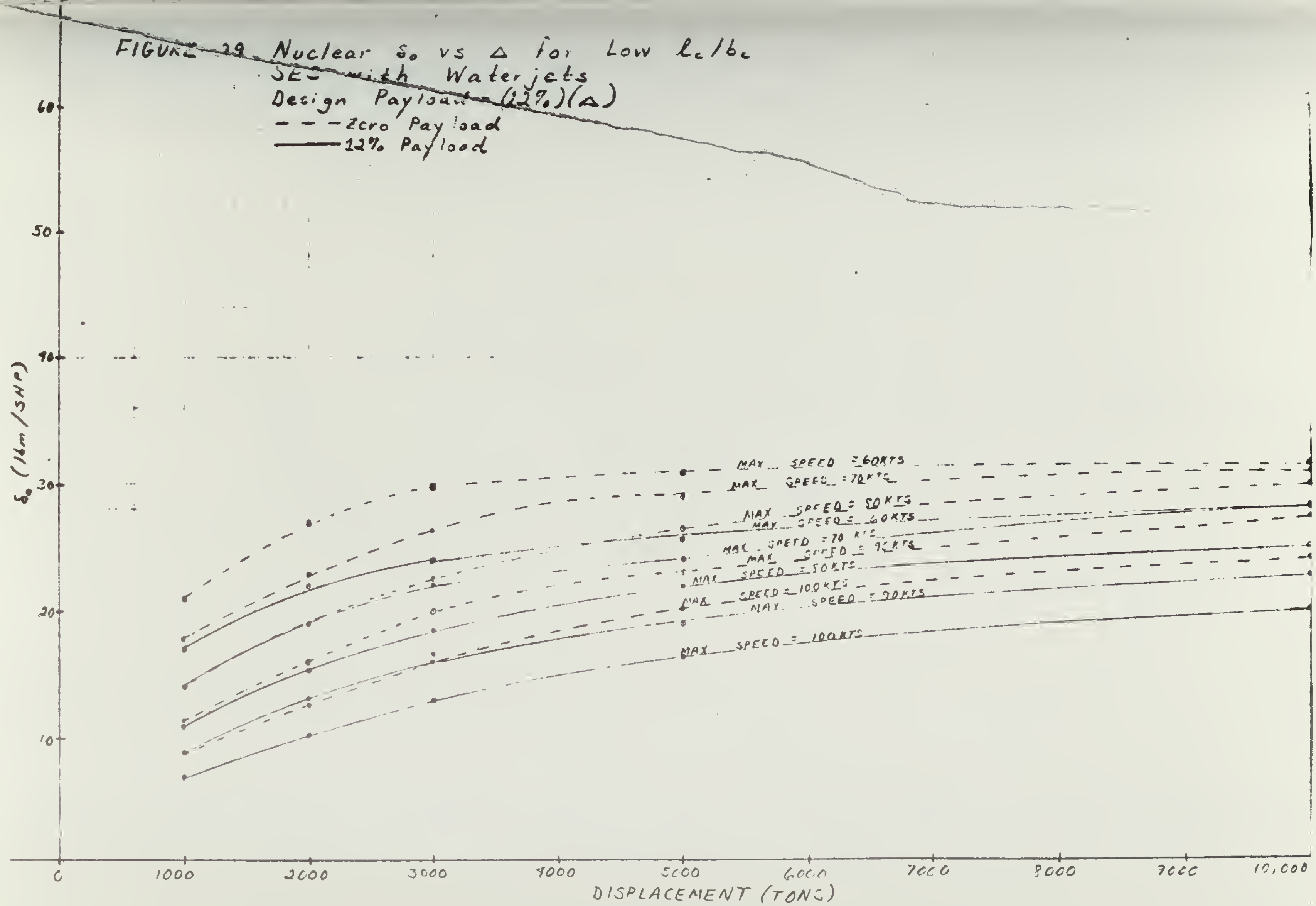


FIGURE 29 Nuclear S_o vs Δ for Low l_c/b_c SES with Waterjets

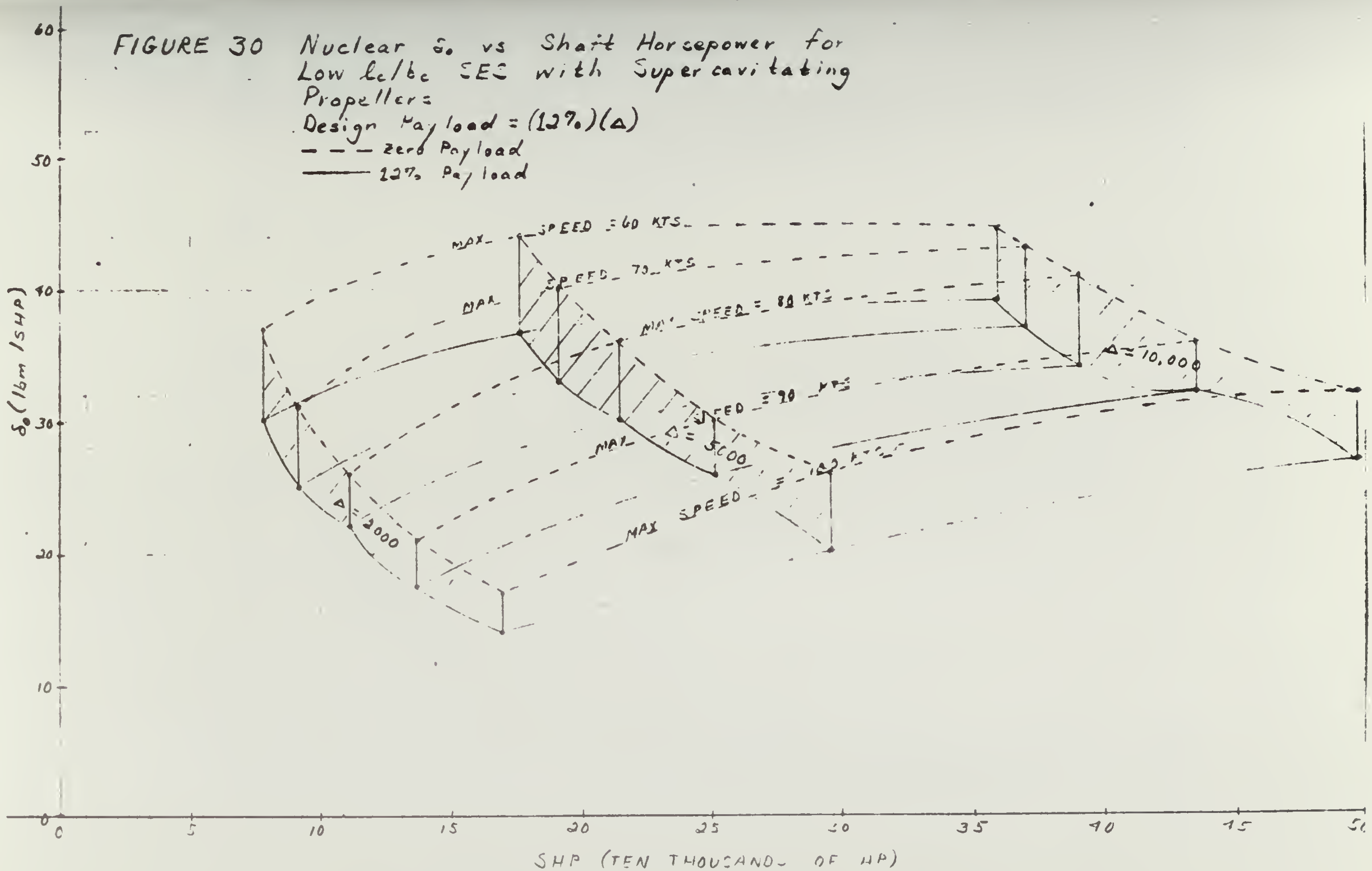


FIGURE 30 Nuclear δ_o vs Shaft Horsepower for Low l_c/b_c SES with Supercavitating Propellers
Design Payload = (12%)(Δ)
– – – zero Payload
—— 12% Payload

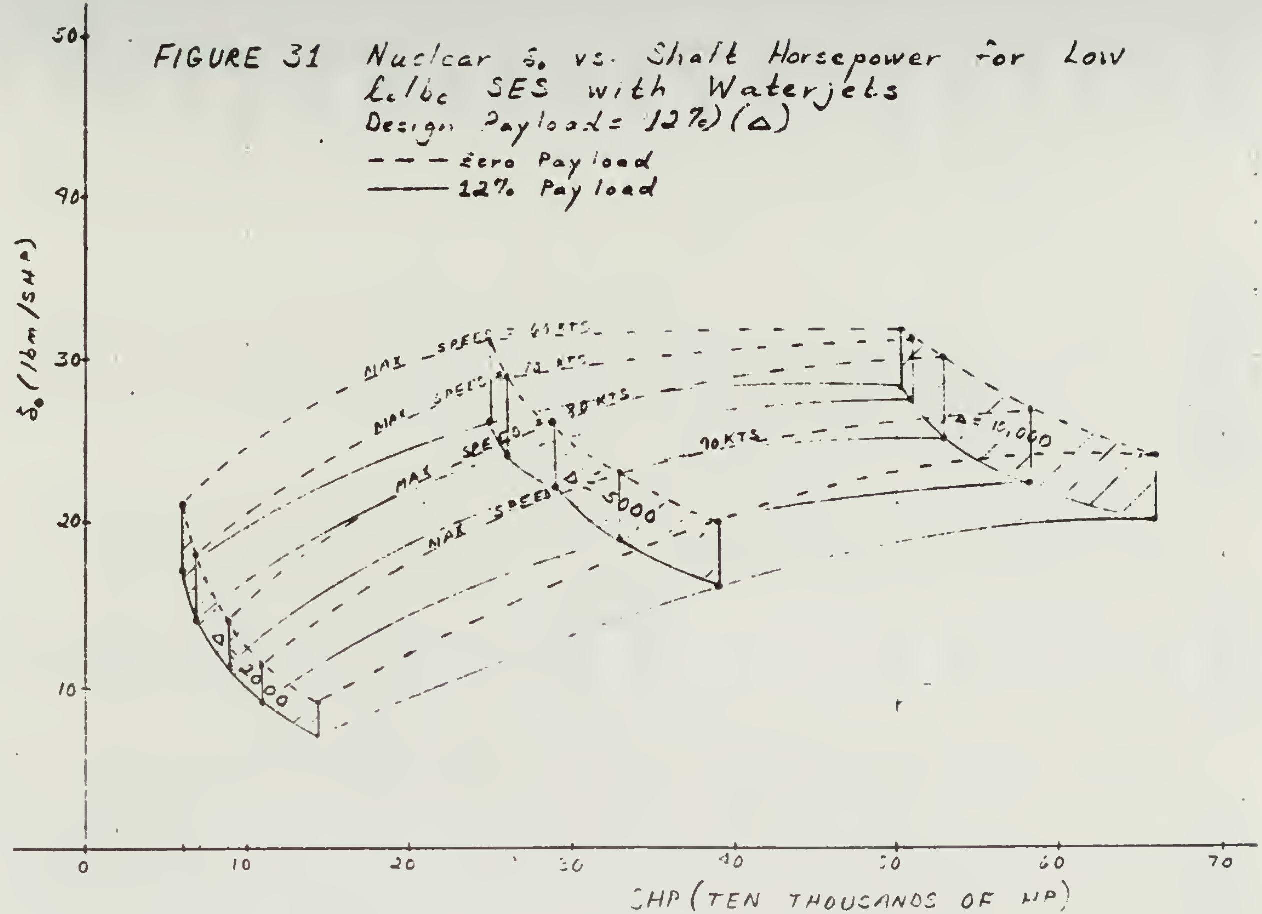


FIGURE 31 Nuclear δ_o vs. Shaft Horsepower for Low L_c/b_c SES with Waterjets
Design Payload = 12%) (Δ)

TABLE 13

SES δ_o LIMITS (SUPERCAVITATING PROPELLER)

DISPLACEMENT (TONS)	PAYLOAD WEIGHT FRACTION (%)	MAX SPEED (KTS)	δ_o (lbm/SHP)
2,000	0	60	37
2,000	12	60	30
2,000	0	70	31
2,000	12	70	25
2,000	0	80	26
2,000	12	80	22
2,000	0	90	21
2,000	12	90	17
2,000	0	100	17
2,000	12	100	14
5,000	0	60	44
5,000	12	60	36
5,000	0	70	40
5,000	12	70	33
5,000	0	80	36
5,000	12	80	30
5,000	0	90	30
5,000	12	90	26
5,000	0	100	26
5,000	12	100	20

ships became volume and stability limited. "Volume limited" means that every useable cubic foot of space inside the whole envelope of the ship, including the superstructure is housing an essential function. Additional space would require increased dimensions. "Stability limited" means that the ship just meets minimum accepted stability standards such as Goldberg & Tucker (G5). Any addition of weight topside, for instance, would require increased beam or ballast weight low in the ship.

An effort was made to investigate viable ships with weight fraction payloads from zero to 12% since beyond these limits, the weight equations suffer from feedback inaccuracies. For instance, Weight Group 3 is a strong function of the payload, but the parametric weight equations utilized for this weight group were primarily a function of SHP and/or Δ, assuming a normal payload weight fraction of 9 - 13%. True point designs would have had to employ successive design iterations to accurately access the effects of greater weight fraction payloads.

It should also be noted that since the conventional displacement ship and the hydrofoil weight models were based on actual ships with exception of the HOC, whereas the SES and HPDS due to the state-of-the-art had to be based on design studies,meaning that the SES and HPDS models may be overly optimistic.

3.7 Summary of Naval Architectural Results

Through a computerized sensitivity analysis utilizing parametric weight equations, the effects of the propulsion plant on high performance ships were examined. Fossil-fueled plants and nuclear propulsion plants of various specific propulsion weights were examined to determine the

effects of speed and range on payload weight. The analysis substantiated the fact that for high performance fossil-fueled ships, their extremely weight limited nature dictates light weight gas turbine plants to afford adequate payload, range, and speed. The hydrofoil is the most severly weight limited ship due to the heavy price exacted by the foil system weight, which increases as displacement increases.

Domains for installing nuclear plants on these ships with 12% payload weight fraction are summarized below:

1. Conventional displacement ship

DISPLACEMENT	MAX SUSTAINED SPEED (KTS)	δ ALLOWED (lbm/SHP)
2,000	28	45
2,000	40	15
10,000	28	128
10,000	40	30

2. High performance ship (supercavitating propeller)

DISPLACEMENT	FULL SPEED (KTS)	δ ALLOWED (lbm/SHP)
1,000	30	96
1,000	60	20
4,000	30	131
4,000	60	32

3. Hydrofoil (subcavitating foil, supercavitating propeller)

DISPLACEMENT	FULL SPEED (KTS)	δ ALLOWED (lbm/SHP)
230	40	19
230	50	14
1,278	40	35
1,278	50	23

4. SES (l_c/b_c = 2.0, P_c/L_c = 1.5, supercavitating propeller)

DISPLACEMENT	FULL SPEED (KTS)	δ_e ALLOWED (lbm/SHP)
1,000	60	30
1,000	100	14
5,000	60	36
5,000	100	20

Three additional points should be made. First, the general trend, as far as the domains for installing nuclear propulsion plants on ships, indicated that higher weight nuclear propulsion plants can be accomodated only by increasing displacement and/or decreasing speeds. However, the high performance ship analysis indicated that utilizing high performance design criteria as embodied in the design of hydrofoils might possibly allow 120% - 400 % increases specific propulsion weights, assuming there are no structural loading problems. And lastly, if a waterjet propulsion system is substituted for the supercavitating propellers, the reduction in in propulsive coefficient increases the shaft horsepower to such an extent that specific propulsion weight must be lowered 6 to 30 lbm/SHP depending on the ship type, displacement, and speed.

CHAPTER 4

NAVAL NUCLEAR SPECIFIC PROPULSION WEIGHT ANALYSIS

In chapters two and three the domains for installing a nuclear propul-sion plant on a ship were examined, this next chapter will explore possible nuclear propulsion plants for use on high performance ships in terms of their specific propulsion weight and shaft horsepower. Also in this fourth chap-ter these plants are examined to determine their potential in terms of pay-load weight fraction, speed, and displacement for the particular ship types.

.1 Weight Minimization in Naval Nuclear Propulsion Plants

Extensive effort has been devoted to weight minimization in the present aval loop type pressurized water reactors. One avenue has been through ankine cycle parametric optimizations, i.e. selecting the optimum turbine xhaust pressure, main steam temperature, average coolant temperature, and oolant pressure to achieve minimum overall plant weights. Furthermore, the oolant flow rate, number of core passes, the number of reactors, and the umber of loops per reactor have also been examined in detail to achieve inimum weight within the restrictions of safety and other design considerations.

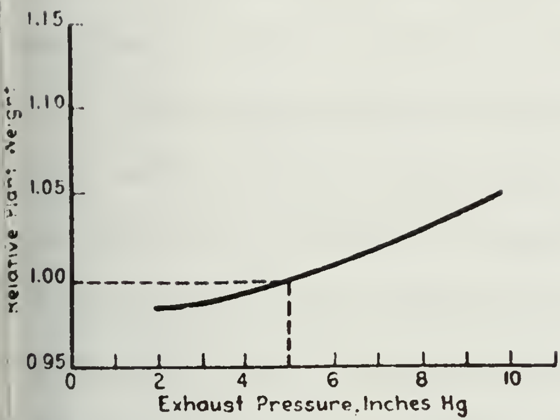
An example explains qualitatively one of these optimizations. If the urbine-exhaust temperature or back pressure is increased, the main condenser nd turbine size is reduced at the expense of plant thermal efficiency. The ecessary increase in heat output to maintain a constant shaft horsepower aturally requires size, capacity, and weight increases in the condensate, eedwater, and heat-generating systems and equipment. In a fossil-fueled lant the effect of efficiency is felt primarily in fuel economy, but in a uclear plant the most important effect is the increase in the size of the

eactor, steam generators, and coolant system. These components are not nly heavy in themselves, but any increase in their size is reflected in ncreases in the size and weight of the coolant system shielding. The esult is a net increase in overall weight for the plant as the back pressure ncreases, as shown in Figure 32. Figures 33 - 35 summarize other typical aval pressurized water reactor parametric optimizations. (R11)

To effect drastic reductions in the overall nuclear specific weight, owever, the energy generation portion of the nuclear system must somehow e reduced since it accounts for over one half of the overall specific ropulsion weight δ_o. The energy generation portion includes the reactor d its shielding. If an examination is made of the four variables which imarily influence the shielding weight, which accounts for about 50% of e energy generation weight, an avenue for weight reduction will be revealed.

1. Radiation levels outside the shielding

Extensive studies have been made to determine the weight savings ssible if allowed radiation (10 CFR 20) levels were increased. However, en if the radiation levels were increased three-fold to lethal doses at e surface of the reactor shield, only a 10% shield weight savings would cur. (R11) Although some studies in the nuclear powered airplane project ntemplated schemes in which just the passenger compartment was shielded, is does not appear feasible for a naval ship that must be maintained at a for long periods. Therefore, with the knowledge that weight savings are ll and in recognition of recommendation that radiation levels be kept as w as practicable due to the uncertainty of somatic and genetic radiation fects, this avenue has attracted few converts for reducing weight.



G. 32 EFFECT OF EXHAUST PRESSURE ON NUCLEAR PROPULSION PLANT WEIGHT

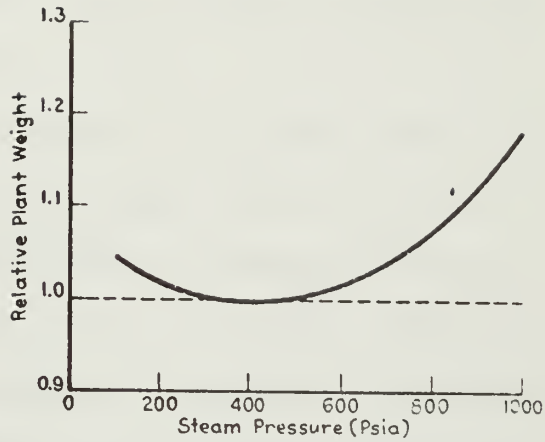
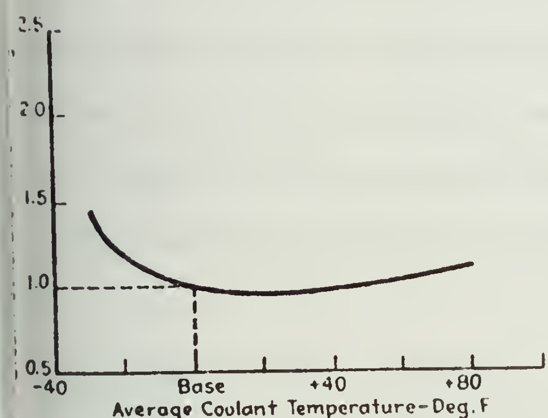


FIG. 33 EFFECT OF STEAM PRESSURE ON NUCLEAR PROPULSION PLANT WEIGHT



F. 34 VARIATION OF STEAM-GENERATOR WEIGHT WITH AVERAGE REACTOR COOLANT TEMPERATURE

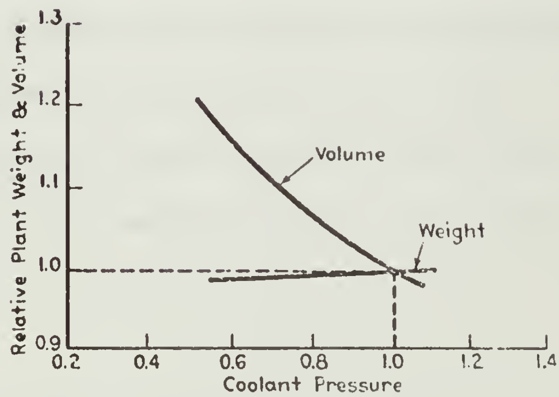


FIG. 35 EFFECT OF VARIATION IN PRIMARY COOLANT PRESSURE ON REACTOR PLANT WEIGHT AND VOLUME

2. Materials for shielding

The radiations of primary concern biologically are fast neutrons and ;amma rays. Although the hydrogenous shield materials are light, most of the reight of the shield is occasioned by the requirement to attenuate the gamma radiation. Although the amount of material required depends upon its exact composition and upon the energy of the gamma radiation, one may use a thick vall of light material (such as water or concrete), or a thinner wall of ieavier material (such as lead), but the total weight of the wall will be early the same in any case. A shielding material of high density such as ead can be packed close around the reactor to lower the weight. However, hen the additional structural material required to support this concentrated eight and to supply the structural strength that lead lacks, the weight avings are negated.(R11).

3. Type of fluids used to cool the reactor

Since the reactor coolants contain activation products which must be iielded, lead, bismuth, various organic fluids, and helium have been suggested coolants since they are nearly nonradioactive in the pure state. The oblem though is that corrosion, impurities, and possible fuel clad failures ill mean that some radioactive sources in the coolant loops will be present. 11)

4. Plant and ship arrangement

Proper arrangement of the plant systems and compacting the core is obably the most plausible direction in which to reduce weight yet maintain required standards. If the reactor is kept as compact as possible through reactor weight density and high reactor power densities, the reactor ght W_{RX} will be minimized.

$$W_{RX} = \frac{\rho_t \, P_{th}}{\rho_p \, 2240} \quad (\text{TONS}) \tag{4.1}$$

where $P_{th} = 7.47 \times 10^{-4} \, \frac{SHP_{TOTAL}}{\eta_t} \quad (MW_t) =$ thermal power

SHP = shaft horsepower

η_t = thermal cycle efficiency

ρ_t = reactor weight density (lbm/ft^3)

ρ_p = reactor power density (MW/ft^3)

Improvements over present naval reactor values of W_{RX} might be provided y high temperature reactors such as the He and Na - cooled fast reactors. here are examples discussed further in Section 4.3. Another method is to roup the most radioactive sources close together around the reactor with ess radioactive components outside of them and/or eliminate the need for secondary shield. As opposed to the loop type naval pressurized water eactor the integral type Babcock & Wilcox "CNSG" (H3) and the Combustion ngineering "UNIMOD" (H3) designs eliminate the need for a secondary shield y containing the reactor core and control rods, steam generator, pressurizer team space, and all internal supports for the core, steam generator, and ontrol rod drive line within the reactor pressure vessel.

Therefore, cores can be compacted by going to high temperature, high ower density systems. Since primary shield weight is proportional to the ube of the reactor radius, shielding weight is decreased also. For the ntegral pressurized water reactor, another method to reduce weight is to roup the piping, pressurizer, and other primary components within the pressure essel and thus eliminate the requirement for secondary shielding.

2 Method of Nuclear Propulsion Weight Analysis

As shown in Figure 36, possible nuclear propulsion plants can be broken down into three major subdivisions:

1. Energy generation group --- the reactor core, reactor coolant loop piping, reactor support components, and the heat exchanger where applicable
2. Energy conversion groups --- the cycle energy conversion method (Rankine cycle, magnetohydrodynamics, etc.)
3. Energy transmission group --- the method utilized to change energy into the ship propulsion force

Figure 36 summarizes possible analysis routes; the numbers indicate a particular system as summarized in Tables 14 - 16. For instance under energy generation, the number one (1) indicates the pressurized water reactor energy generation method.

The weight estimation relationships shown in Tables 14 - 16 were derived from a consensus of various referenced sources. The weight estimates for the energy generation groups were given as a specific weight, i.e. normalized by shaft horsepower for a given thermal efficiency. The energy conversion and the energy transmission group weights were a "best" estimate value or an equation that provided results consistent with various sources. It should be emphasized that the relationships were *gross* estimates in that they were in most cases only power dependent. Furthermore, as detailed in Appendix C, weight estimates were also made for repair and propulsion operating fluid weights, weight for collision/structural bulkheads, added weight for foundations, and added weight for the increased electrical requirements due to the nuclear propulsion system.

FIGURE 36 Nuclear Propulsion System Breakdown

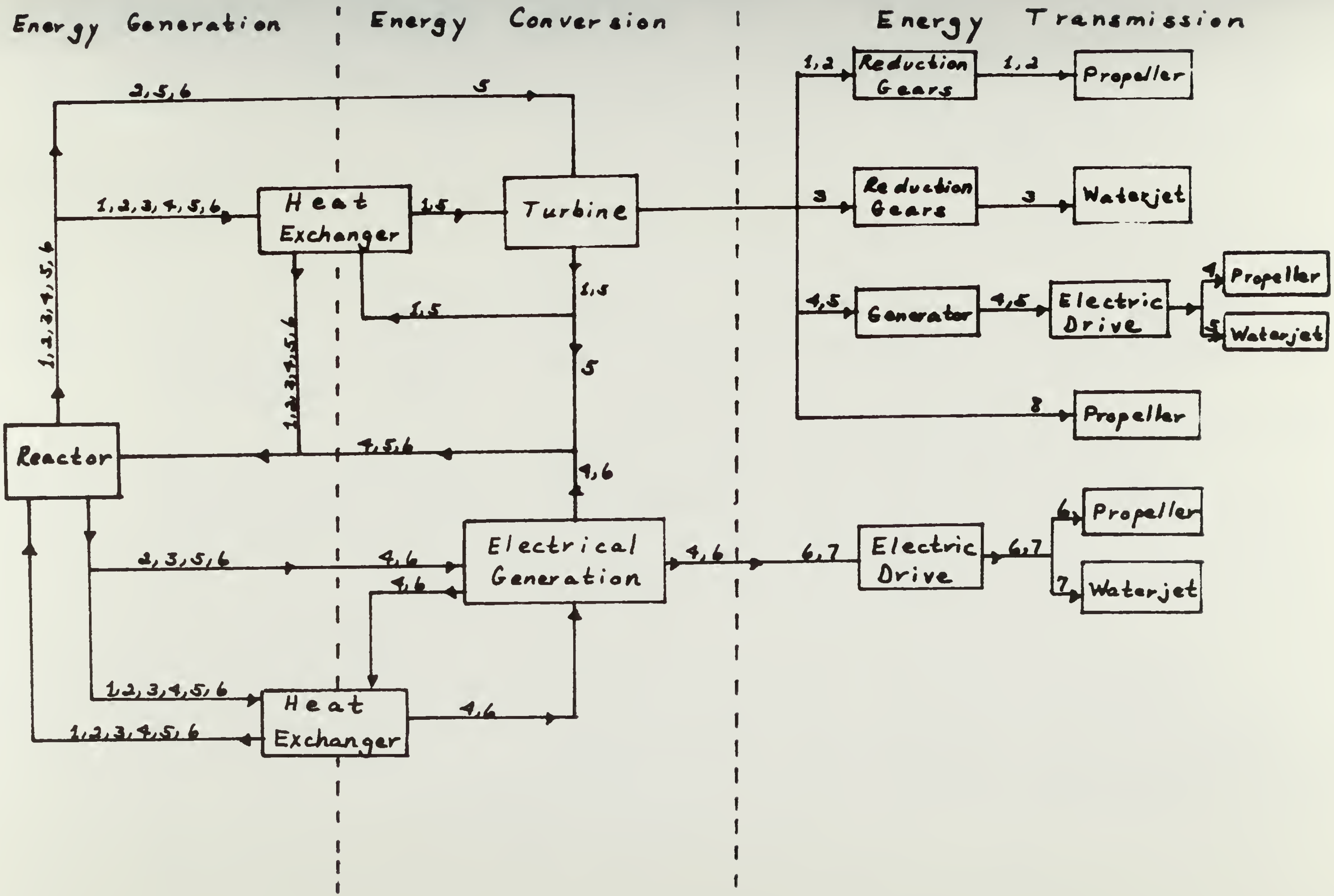


TABLE IV

Energy Generation Schemes

Matrix #	Scheme Description	Weight Estimation Relationships: δ_{21}	
1	Pressurized Water Reactor	Naval Pressurized Water Reactor 60.0 lbm/SHP for 60,000 SHP	(B6) $\eta_{cycle} = 0.27$
		"UNIMOD" 32.1 lbm/SHP for 30,000 SHP; 22.4 lbm/SHP for 60,000 SHP	(B2) $\eta_{cycle} = 0.27$
		"CNSG" 44.2 lbm/SHP for 70,000 SHP	(B2) $\eta_{cycle} = 0.29$
2	He-Cooled Fast Reactor (F2)	14.2 lbm/SHP for 100 MW_t reactor 8.7 lbm/SHP for 200 MW_t reactor 6.6 lbm/SHP for 300 MW_t reactor 5.4 lbm/SHP for 400 MW_t reactor	(F2) $\eta_{cycle} = 0.42$
3	Na-Cooled Fast Reactor (F2)	12.64 lbm/SHP for 100 MW_t reactor 7.30 lbm/SHP for 200 MW_t reactor 5.44 lbm/SHP for 300 MW_t reactor 4.45 lbm/SHP for 400 MW_t reactor	(F2) $\eta_{cycle} = 0.41$ He-Turbine Conversion
		12.45 lbm/SHP for 100 MW_t reactor 7.30 lbm/SHP for 200 MW_t reactor 5.44 lbm/SHP for 300 MW_t reactor 4.45 lbm/SHP for 400 MW_t reactor	(F2) $\eta_{cycle} = 0.41$ Two-Phase Liquid Metal MHD Conversion

Energy Generation Schemes

Matrix #	Scheme Description	Weight Estimation Relationships	δ_{21}
4	Molten Salt Reactor (A.P. Fraas)	37.35 lbm/SHP for 25 MW_t 21.79 lbm/SHP for 50 MW_t 13.38 lbm/SHP for 100 MW_t 8.72 lbm/SHP for 200 MW_t 5.91 lbm/SHP for 400 MW_t	(R2) $\eta_{CYCLE} = 0.27$
5	Water-Moderated He-Cooled Reactor (GE 630-A MK V)	37.7 lbm/SHP for 27,300 SHP	(R2) $\eta_{CYCLE} = 0.337$
6	Graphite Moderated Gas Cooled Epithermal Reactor	34.4 lbm/SHP for 25,000 SHP 19.5 lbm/SHP for 50,000 SHP 14.5 lbm/SHP for 100,000 SHP 9.7 lbm/SHP for 200,000 SHP 8.4 lbm/SHP for 300,000 SHP 7.4 lbm/SHP for 400,000 SHP	(R2) $\eta_{CYCLE} = 0.35$

TABLE 15

Energy Conversion Schemes

Matrix #	Scheme Description	Weight Estimation Relationships δ_{22}
1	Rankine Cycle (Steam)	9.1 lbm/SHP for conventional systems 14.1 lbm/SHP for nuclear systems (S7, G6, examination of existing naval steam propulsion systems)
2	Feher Cycle	Not Utilized
3	Potassium Vapor Turbine	Not Utilized
4	LMMHD (DC ≤ 100,000 HP, AC > 100,000 HP with 10% decrease in isentropic efficiency)	5.0 lbm/SHP (R2, P5, examination of existing Brayton turbomachinery)
5	LMMHD & Gas Turbine Dual Cycle	5.0 lbm/SHP (R2, P5, S7)

Energy Transmission Schemes

Matrix #	Scheme Description	Weight Estimation Relationships δ_{23}
1	Reduction Gears — Fixed Pitch Propeller	Transmissions: Helical locked train double reduction gears 9.2 lbm/SHP (H3, G14, examination of existing gear systems) Planetary gears = $[0.85(SHP)+2500]/SHP$ (R10, G14) Propeller: 0.9 lbm/SHP (M7, G14, R10, H3)
2	Reduction Gears — Variable Pitch Propeller	Transmissions: Planetary gears = $\frac{[0.35(SHP)+2500]}{SHP}$ (R10, G14) Propeller: 1.7 lbm/SHP (Examination of existing systems)
3	Waterjet Pump	Transmission = $[0.28(SHP)+1200]/SHP$ (R10, G14) Waterjet = $410[(SHP)\times 10^{-3}]^{1.46}/SHP$ (R10, G14)
4	Superconducting Generator & Motors — Fixed Pitch Propeller	Superconducting generator 0.39 lbm/SHP Superconducting motors 1.17 lbm/SHP He-liquefier system 0.23 lbm/SHP Braking resistors 0.07 lbm/SHP Transmission bus 0.01 lbm/SHP Cycloconverter 0.51 lbm/SHP 2.38 lbm/SHP (R10, R2, G13, S7) Propeller: 0.9 lbm/SHP (M7, G14, R10, H3)

TABLE 16 (Cont.)

Energy Transmission Schemes

Matrix #	Scheme Description	Weight Estimation Relationships δ_{23}
5	Superconducting Generator & Motors → Waterjet	Superconducting generator 0.39 lbm/SHP Superconducting motors 1.17 lbm/SHP He-liquefier system 0.23 lbm/SHP Transmission bus 0.01 lbm/SHP Cyclo converter 0.51 lbm/SHP (R10, R2, G13, S7) 2.31 lbm/SHP Waterjet $= 410\left[(SHP)\times 10^{-3}\right]^{1.46}/SHP$ (R10, G14)
6	Superconducting Motors ⊥ Waterjet	Superconducting motors 1.17 lbm/SHP He-liquefier system 0.23 lbm/SHP Transmission bus 0.01 lbm/SHP Cycloconverter (R10, R2, G13, S7) 0.51 lbm/SHP 1.92 lbm/SHP Waterjet $= 410\left[(SHP)\times 10^{-3}\right]^{1.46}/SHP$ (R10, G14)
7	Superconducting Motors — Fixed Pitch Propeller	Superconducting motors 1.17 lbm/SHP He-liquefier system 0.23 lbm/SHP Transmission bus 0.01 lbm/SHP Cycloconverter (R10, R2, G13, S7) 0.51 lbm/SHP 1.92 lbm/SHP Propeller: 0.9 lbm/SHP (M7, G14, R10, H3)
8	Direct Drive Turbines — Fixed Pitch Propeller	Not Utilized

After this information had been collected, combinations of the energy eneration, energy conversion, and energy transmission groups were analyzed o determine their compatability. For the compatible combinations, a cycle fficiency was estimated based on the inlet turbine or magnetohydrodynamic enerator inlet temperature and the type of cycle. Finally, the overall pecific propulsion weight δ_0 was determined for the given shaft horsepower y adding the specific energy generation weight δ_{21} the specific energy conersion weight δ_{22}, the specific energy transmission weight δ_{23}, the specific epair and propulsion operating fluid weight δ_{24}, the specific weight for ollision/structural bulkheads δ_{114}', specific added weight for foundations δ_{112}', and specific added weight for the increased electrical requirements δ_3'.

$$\delta_0 = \delta_{21} + \delta_{22} + \delta_{23} + \delta_{24} + \delta_{112}' + \delta_{114}' + \delta_3' \qquad (4.2)$$

where

$$\delta_{21} + \delta_{22} + \delta_{23} + \delta_{24} = \delta_2 = \text{specific machinery weight} \qquad (4.3)$$

$$\delta_{112}' + \delta_{114}' = \delta_1' = \text{specific hull increases} \qquad (4.4)$$

Rcall from Section 2.4.2, for the fossil-fueled ship δ_1' and $\delta_3' \longrightarrow 0$ ie. $\delta_0 = \delta_2$ for the fossil-fueled ship.

43 Energy Generation Group

The reactor systems investigated are briefly described in this section nd the references from which the weight estimatation relationships were erived are enumerated.

.3.1 Pressurized Water Reactors

The naval pressurized water loop reactor was described in section 2.4.1. he weights were estimated from the Russian summary of U. S. submarine esign (B6). In addition there are two integral type reactors that show romise, the Babcock & Wilcox "CNSG" (H3) and the Combustion Engineering UNIMOD" (H4). The integral type reactors achieve greater compaction by mploying a self-pressurized reactor with the heat exchanger located within he reactor vessel. The elimination of external primary loop components educes the radioactive volume requiring shielding and, hence, the shield ize and weight. The "CNSG" is somewhat heavier than the "UNIMOD" since ie "CNSG" shielding surrounds the containment and pressure suppression amber whereas the "UNIMOD" design relies primarily on shielding next to ie pressure vessel and inside the containment vessel. There is no decisive dvantage of one PWR reactor over the other. Weights were estimated from a tudy done by Bauman (B2).

4.3.2 He-Cooled Fast Reactors

A He-cooled fast reactor adopted by the Office of Naval Research for a reliminary design of compact reactors ranging from 100 MW to 400 MW was xamined. (F2) Appendix C contains a detailed design data and weight listing nd compact core configuration for this reactor.

4.3.3 Na-Cooled Fast Reactors

In another study by the Office of Naval Research, a Na-cooled fast reactor preliminary design was examined (F2). Due to the presence of the radioactive isotope Na^{24} in the primary coolant it is particularly inadvisable t attempt a direct cycle liquid sodium magnetohydrodynamics cycle. Therefore,

intermediate heat exchangers for a helium gas turbine conversion system and magnetohydrodynamics were also sized. Appendix C contains a detailed esign data listing and major component weight breakdown.

.3.4 Molten Salt Reactors

In a study by A. P. Fraas, (R2) a series of molten salt reactors were xamined. Appendix C contains the weight breakdown for this high temperature nergy generation source.

.3.5 He-Cooled Water Moderated Reactors

Applying technology developed for the Aircraft Nuclear Propulsion rogram between 1951 and 1961 to the design of a nuclear plant for merchant hip, General Electric developed the GE 631A Mark V design. The 631A is a igh temperature, gas-cooled (helium at 830 psia), water moderated plant hat can produce steam at any desired level of pressure and temperature up o 1500 psig and 1000 F. Overall thermal efficiency of the plant using he highest steam conditions is 33.7%; weight of the containment vessel and ts contents and external shielding is about 460 tons for a 27,300 shaft orsepower plant.

43.6 He-Cooled Graphite Moderated Reactors (R2)

A study of an advanced light-weight reactor was carried out by a team o Westinghouse and Los Alamos Laboratory engineers and scientists. A aphite fuel element reactor based upon the NERVA program and a closed lium Brayton cycle power conversion system with regeneration and intercooling s selected.

The main helium flow path is shown in Figure 37. Reactor outlet onditions of 1700° F and 1500 psia were chosen to provide an attractive ycle efficiency which can be achieved within the expected capability of uperalloy materials without requiring cooling of the turbine blades.

The molecular sieve and cooled charcoal bed reduce the activity in the rimary system due to fission products which may be released by the nuclear uel. The essentially clean helium from the charcoal bed is returned to the ycle during steady state operations or relieved to storage volumes to chieve power output reduction (with the reactor automatically controlled o maintain the desired temperature). Helium can be valved from these storage olumes into the primary flow path at the low pressure compressor inlet to chieve a power increase. The emergency cooling system removes decay heat ithout external power and transfers the heat to its own intermediate heat ransfer system and thence to ambient air through heat exchangers. Heat ejection from the precoolers and intercoolers is to an intermediate heat-ransfer system which in turn rejects heat to seawater through a seawater eat exchanger. The nuclear reactor along with the two power conversion ckages, radiation shielding and containment are shown in Figure 38. This it at the 140,000 SHP rating is 32 feet long, 18 feet wide, and 34 feet gh. The auxiliaries, not shown in this figure, are estimated to require ,700 cubic feet additional volume. Cross sections of the 70,000 SHP wer conversion module and the 300 MW reactor subsystems are shown in Figures and 40. A variation of the system employing a horizontal arrangement as own in Figure 41 was also examined, but had a 10% weight penalty as compared the vertical arrangement.

FIGURE 37 Helium - Cooled Graphite Moderated Reactor Cycle (R2)

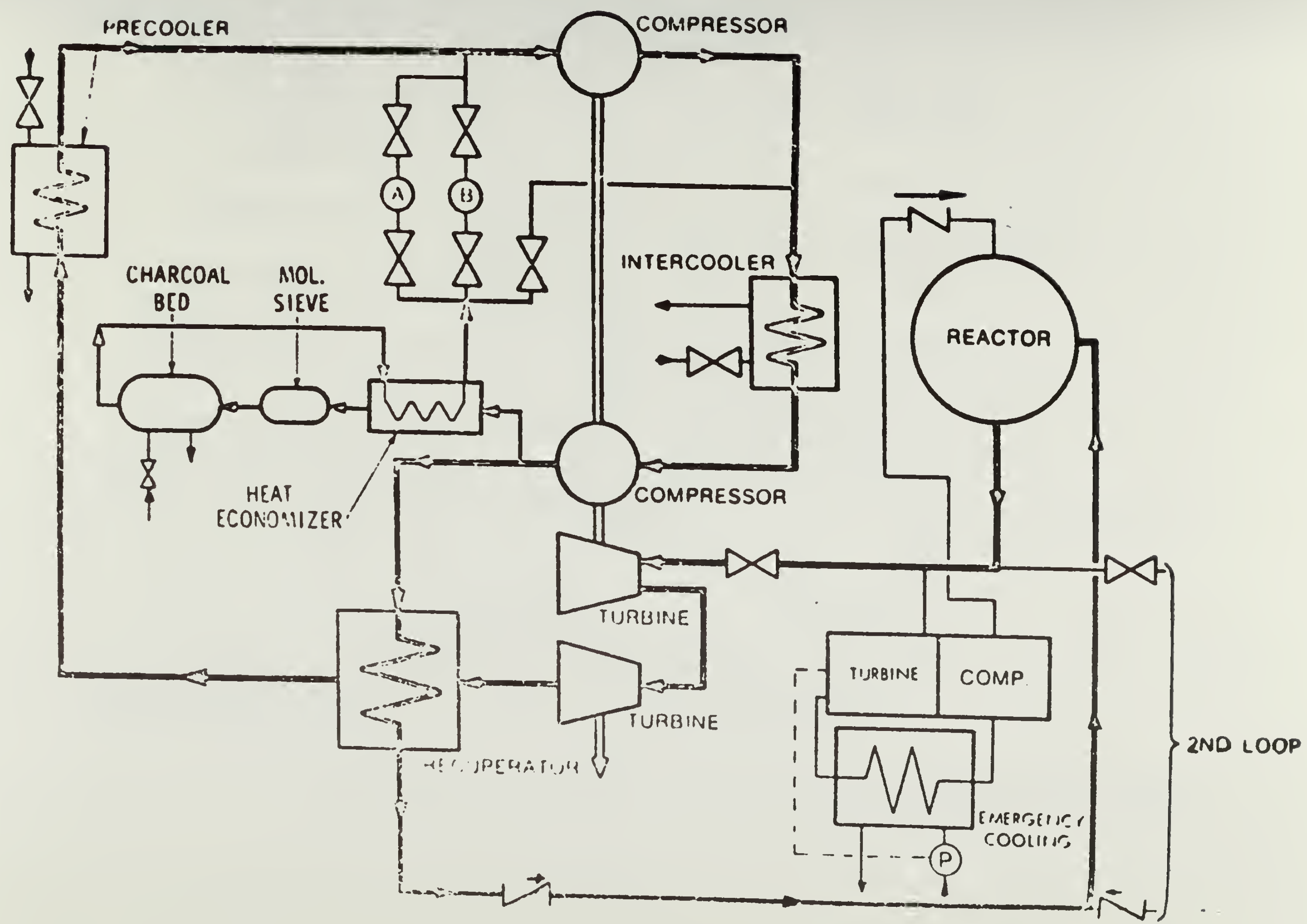


FIGURE 38 Helium-Cooled Graphite Moderated Vertical Reactor Profile (R2)

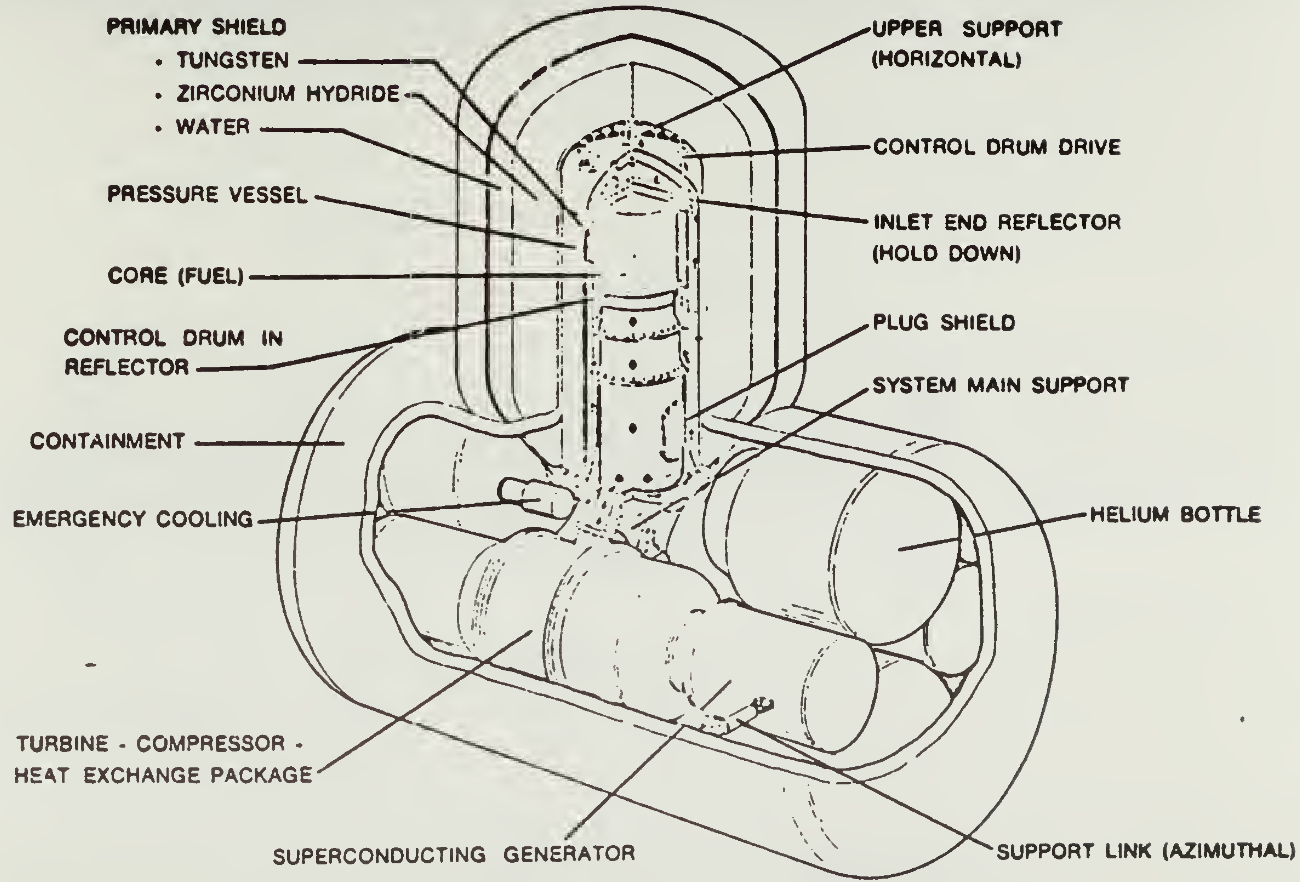


FIGURE 39 Helium-Cooled Graphite Moderated Reactor Turbine-Compressor Package (R2)

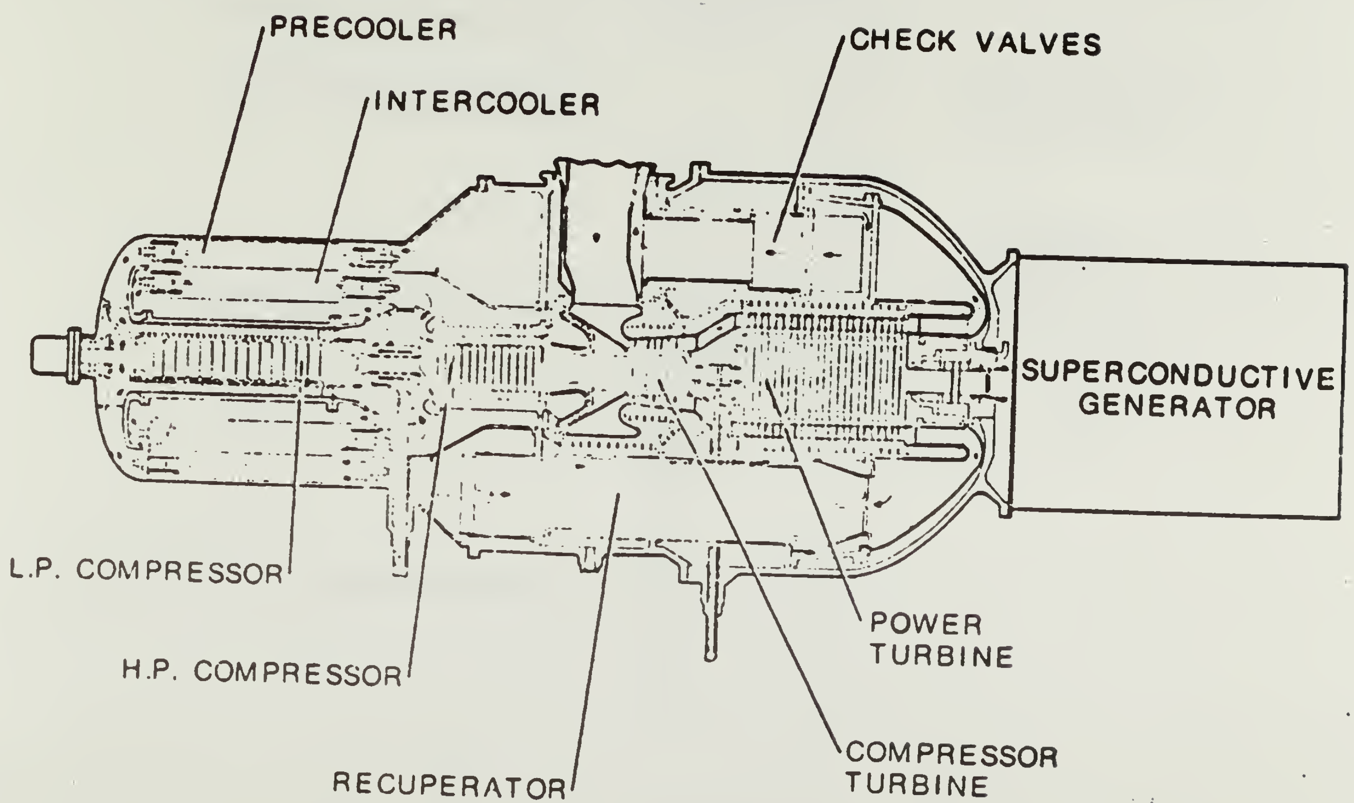


FIGURE 40 Helium-Cooled Graphite Moderated Reactor Configuration (R 2)

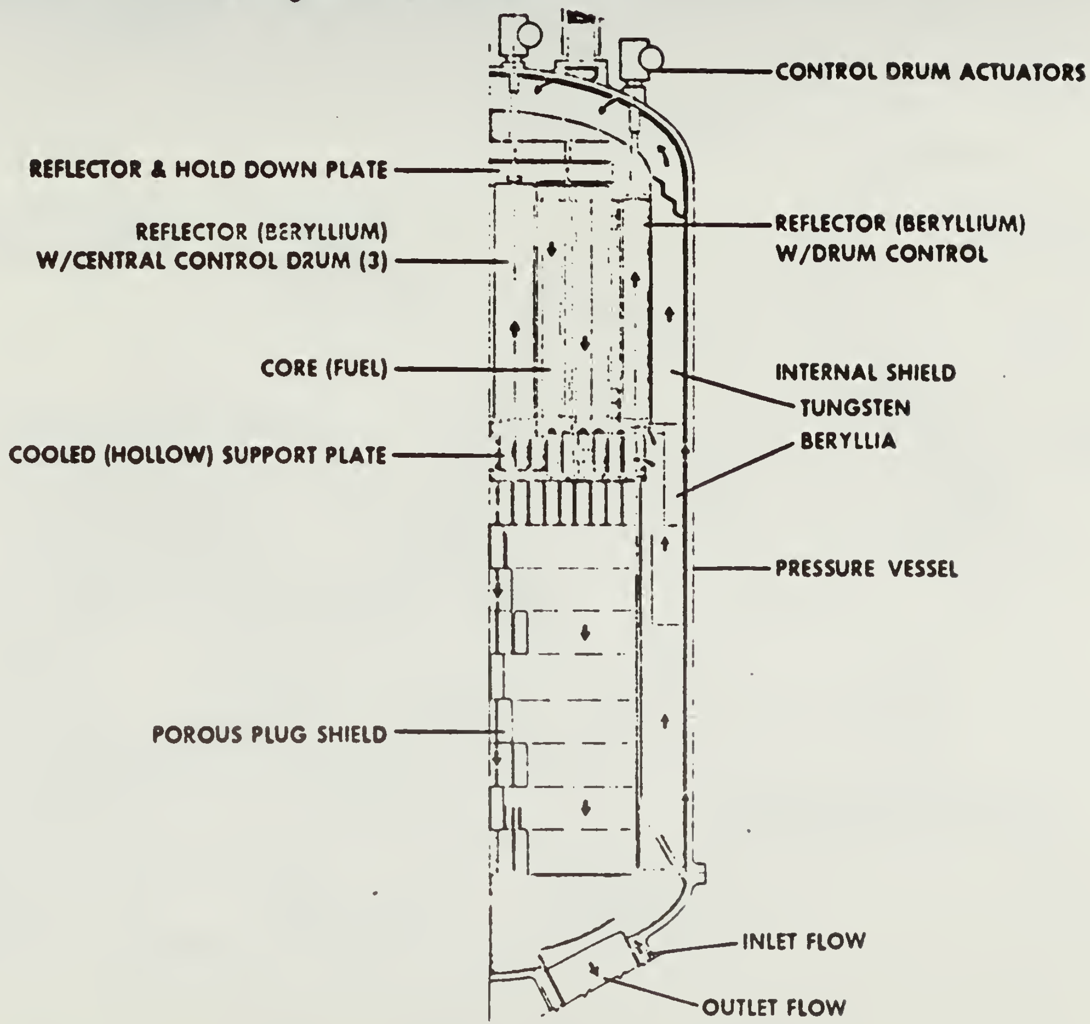
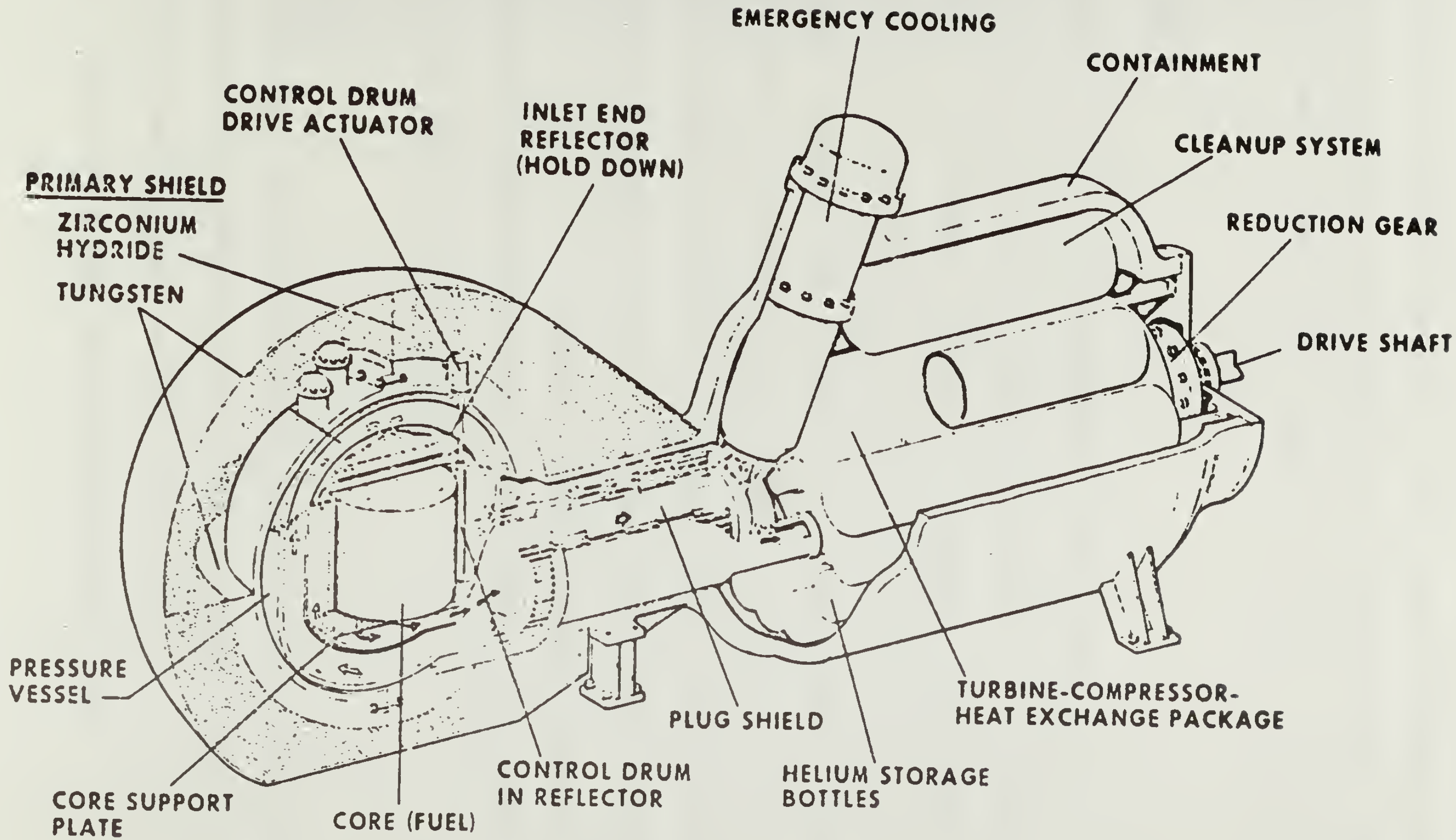


FIGURE 41 Helium-Cooled Graphite Moderated Horizontal Reactor Profile (R2)



4.4 Energy Conversion Groups

Six energy conversion alternatives were considered for light-weight nuclear propulsion plant power production. The options considered were the Feher cycle, the potassium vapor turbine, steam Rankine cycle, liquid metal magnetohydrodynamics, LMMHD & gas turbine dual cycle, and Brayton turbomachinery.

4.4.1 Rankine Cycle

The steam Rankine cycle was examined due to the great level of experience with the pressurized water reactor steam cycle. The limiting factor with respect to this cycle, however, in designing light-weight reactors, is the fact that primary coolant must be highly pressurized and invariably turbine inlet steam temperatures will rarely ever exceed 1000°F. Examination of various fossil-fueled and nuclear Rankine cycles revealed that the specific conversion weight was about 9 lbm/SHP for fossil-fueled plants and increased to about 14 lbm/SHP for nuclear plants. The weight increase for nuclear plants was due to the fact that the nuclear plants had higher endurance requirements dictating higher reliabilities and the steam conditions were such that moisture separators were necessary.

4.4.2 Feher Cycle

The Feher cycle is a supercritical cycle that use CO_2 as the working fluid. This cycle was not considered due to the fact that its 80°F condensing temperature was below many regions the Navy would operate in. Furthermore, the high pressure (4000 psi) CO_2 was deemed quite objectionable.

4.4.3 Potassium Vapor Turbine

The Potassium vapor turbine was also rejected since its condensing temperature is such that the primary use of this cycle would be in a topping cycle with steam as the bottoming cycle. A binary cycle would be far too complex and heavy for light-weight nuclear applications.

4.4.4 Liquid Metal Magnetohydrodynamics

Liquid Metal Magnetohydrodynamics (LMMHD) energy conversion systems were conceived in the early 1960's as compact power systems for use in space. Although the two phase generator can be utilized in Rankine, Brayton, or supercritical cycles, the Brayton cycle with maximum temperatures in the range of 1000°- 2000° F was the only one considered due to insufficient knowledge of the other two.

As shown in Figure 42, the cycle uses an inert gas as the thermodynamic working fluid and a liquid metal as the electrical conductor denoted respectively, by g and l in the figure. In operation, the gas and liquid are mixed, and the mixture enters the generator where the expansion of the gas drives the liquid across the magnetic field and generates electrical power. The two phases are separated and both are returned to the mixer through separate loops. The gas phase passes through a regenerative heat exchanger, a reject heat exchanger, is compressed in a multistate compressor, and then passes via the regenerative heat exchanger and the heat source to the mixer. The liquid is recirculated back to the mixer via the heat source by means of a nozzle diffuser system.

FIGURE 42a Basic Two-Phase Liquid Metal Magnetohydrodynamics Cycle (R2)

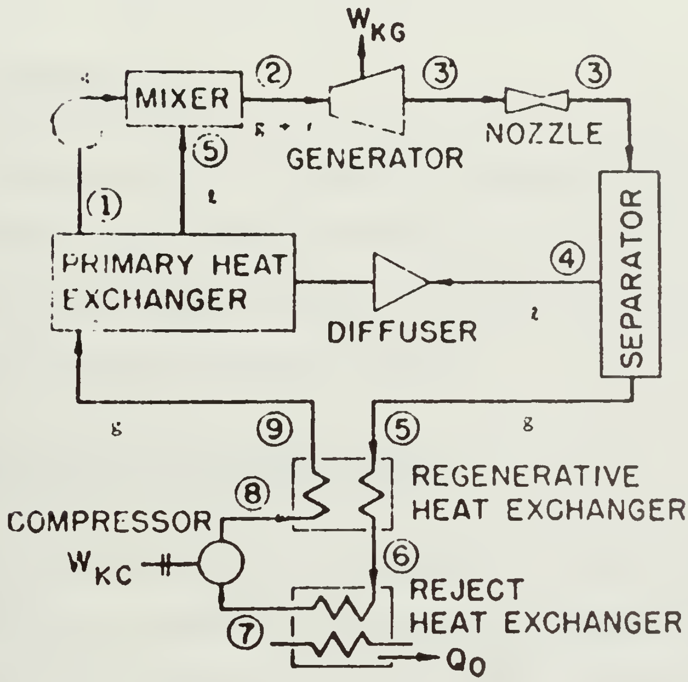
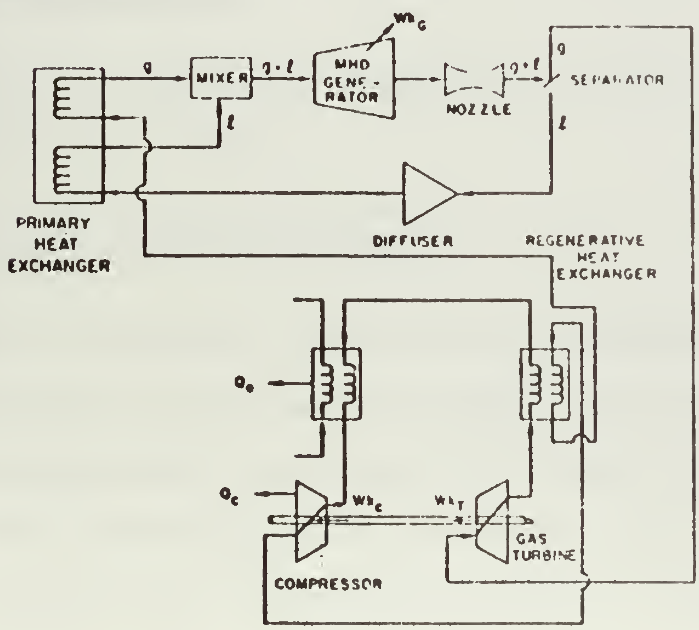


FIGURE 42b Two-Phase Liquid Metal Magnetohydrodynamics and Gas Turbine Dual Cycle (R2)



The estimated weight of a LMMHD conversion system based on the Office of Naval Research estimates (R2,P5) is in the range of 5 lbm/SHP with direct thermal to electrical conversion possible.

4.4.5 Brayton Turbomachinery

Brayton turbomachinery with helium as a working fluid was deemed particularly good for high temperature light-weight reactors. Weight estimates from various sources (R2, R10, S7) indicated about 2.5 lbm/SHP would be required for this conversion system.

4.4.6 LMMHD and The Gas Turbine Dual Cycle

This system is only a slight variation of the basic LMMHD system. By using a gas turbine to drive the compressor as shown in Figure 42b, a significant improvement in cycle performance can be achieved, although the specific conversion weight is still about 5 lbm/SHP.

4.5 Energy Transmission Groups

Examination of various energy transmission groups for propeller and waterjet systems was also effected.

4.5.1 Reduction Gears Fixed Pitch Propeller

Examination of conventional articulated and locked-trains gears and the more recent planetary gears along with various fixed pitch subcavitating and supercavitating propellers was effected. The helical locked train double reduction gears was based on (H3, G14) and examination of existing gear systems which indicated about 9.2 lbm/SHP was required. Planetary gears

eatly reduce this required weight as was indicated by a weight estimating ormula in (R10).

$$\text{Planetary gears specific weight} = [0.85(SHP)+2500]/SHP \qquad (4.3)$$

The propeller was a gross specific weight of 0.9 lbm/SHP (M7, G14, R10, H3). It should be noted this transmission system provides a propulsive coefficient of about 0.7 for surface ships.

5.2 Reduction Gears Variable Pitch Propellers

The variable pitch propeller with its control system was substituted r a fixed pitch propeller for another transmission group. This was cessary for certain group combinations (Brayton turbomachinery), to provide versing capability. Although this eliminated reversing turbines or versing gears, the weight tradeoffs were more or less equal for the fixed tch propeller system and the variable pitch propeller system. The variable tch propeller including servo motors and ancillary equipment required 1.7 lb/SHP.

5.3 Waterjet Pump

The waterjet produces thrust by accelerating water to achieve a net nge in the momentum of the fluid equal to the thrust generated. The ic components of a waterjet propulsion system are (1) an inlet, either or flush, to ingest water and usually an associated inlet diffuser to uce the velocity and increase the pressure of the fluid; (2) a duct, ich transfers the ingested water to the pump and can also further diffuse h flow; (3) a pump, driven by a suitable prime mover, which increases the

ressure and velocity of the water; and (4) a discharge nozzle, which urther increases the water velocity and can be movable for purposes of teering control. Weight estimates were based primarily upon the surface ffect ship waterjet weight estimates. (R10)

$$\text{Transmission specific weight} = \left[0.28\,(\text{SHP}) + 1200\right]/\text{SHP} \qquad (4.4)$$

$$\text{Waterjet Specific Weight} = 410\left[(\text{SHP}) \times 10^{-3}\right]^{1.46}/\text{SHP} \qquad (4.5)$$

Although the waterjet transmission system generally weighs less han a propeller transmission system, the propulsive coefficient of from .4 to 0.5 greatly increases shaft horsepower and consequently energy eneration and conversion weight and fuel weight.

.5.4 Superconducting Generator and Motor

At very low temperatures, in the order of 4.2°K, the resistivity of ertain materials disappears. These superconductors have current carrying apacities up to three orders of magnitude higher than conventional conuctors, allowing great weight and volume savings.

For shipboard installation, a constant speed prime mover drives a ynchronous generator with a superconducting field winding. Cooling of the uperconducting field is provided by circulation of liquid helium. A acuum region surrounding the windings and thermal radiation shield serves s the principal means of insulation. A cycloconvertor, which changes the utput frequency, is the primary means of speed reduction and control. A ynchronous motor, similar to the generator, completes the system. This otor operates at a synchronous speed for a fixed frequency and, as the output frequency from the cycloconverter varies, so does the speed of the motor.

Included in this system is the cryogenic plant which provides liquid elium to the generator and motor to maintain the low temperature necessary or superconductivity. Other components include a transmission bus to ransmit the generated electricity to the cycloconverter and motor, a raking resistor for dynamic braking, and miscellaneous switches and controls.

The weight estimates listed below for this particular transmission were ised on the studies done by Greene(G13) and the SES program weight estimates (10). This system was used with various propulsors to provide propulsion.

SUPERCONDUCTING SPECIFIC WEIGHTS

Superconducting generator	0.39 lbm/SHP
Superconducting motors	1.17 lbm/SHP
Helium liquefier system	0.23 lbm/SHP
Braking resistors	0.07 lbm/SHP
Transmission bus	0.01 lbm/SHP
Cycloconverter	0.51 lbm/SHP
	2.38 lbm/SHP

6 Viable Nuclear Propulsion Alternatives

A matrix (Energy Generation, Energy Conversion, Energy Transmission) of the compatible ombinations was made and the weights totaled to determine the overall ecific propulsion weight for various shaft horsepower ratings. (See Appendix for a detailed weight breakdown of each of these systems). Figure 43 shows e high weight plants, Figure 44 the intermediate weight plants, and Figure 4 the light-weight plants.

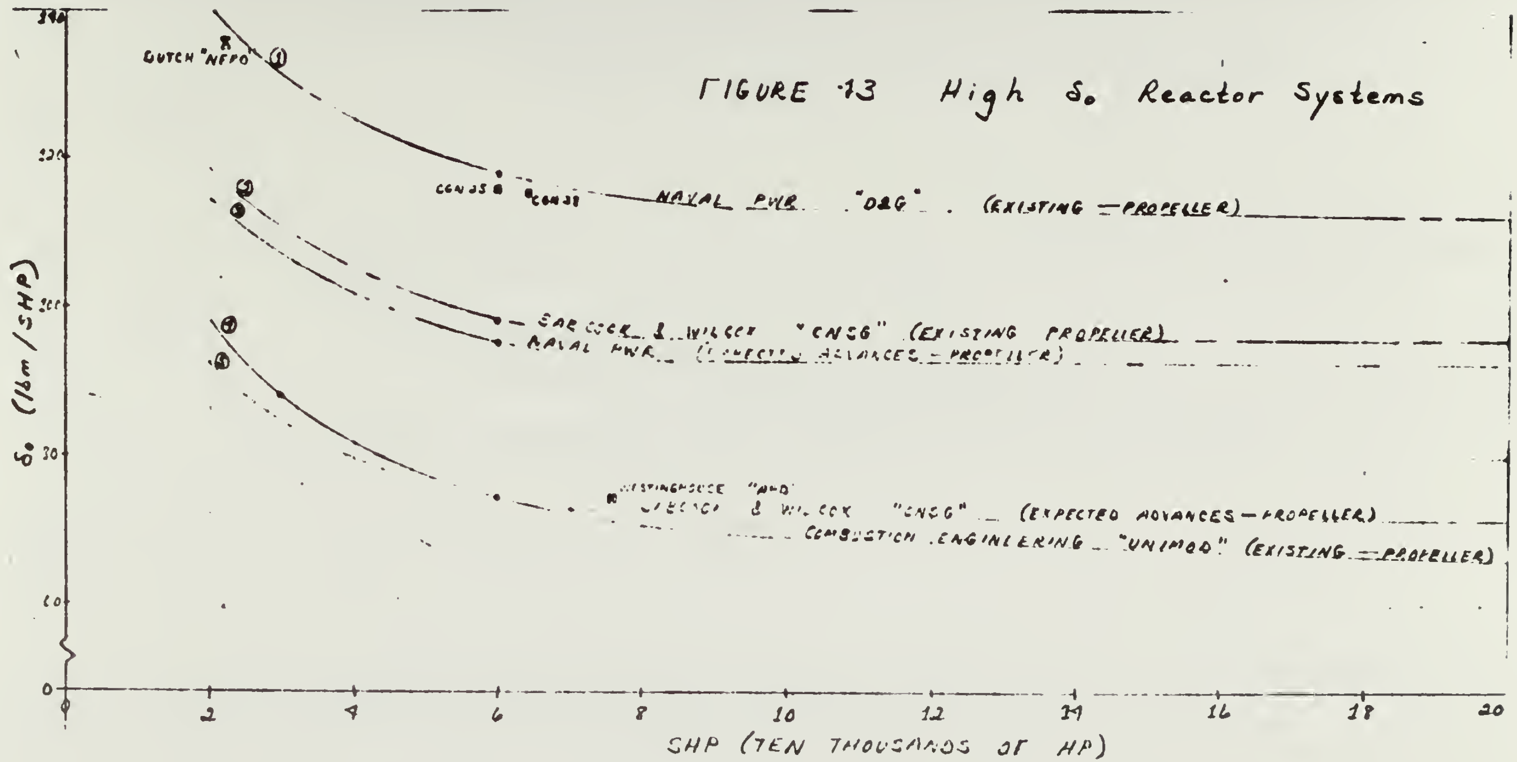


FIGURE 13 High S_o Reactor Systems

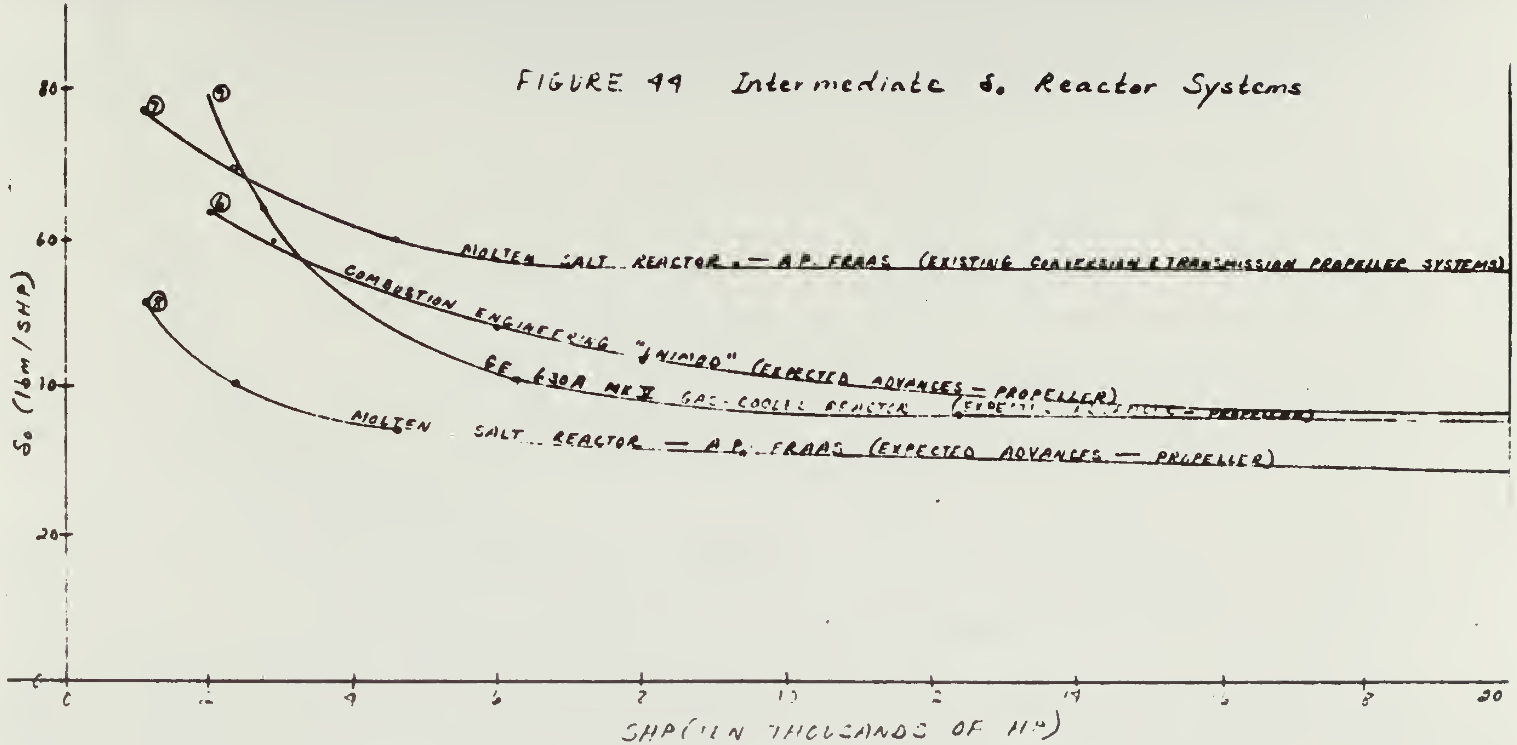


FIGURE 44 Intermediate S_0 Reactor Systems

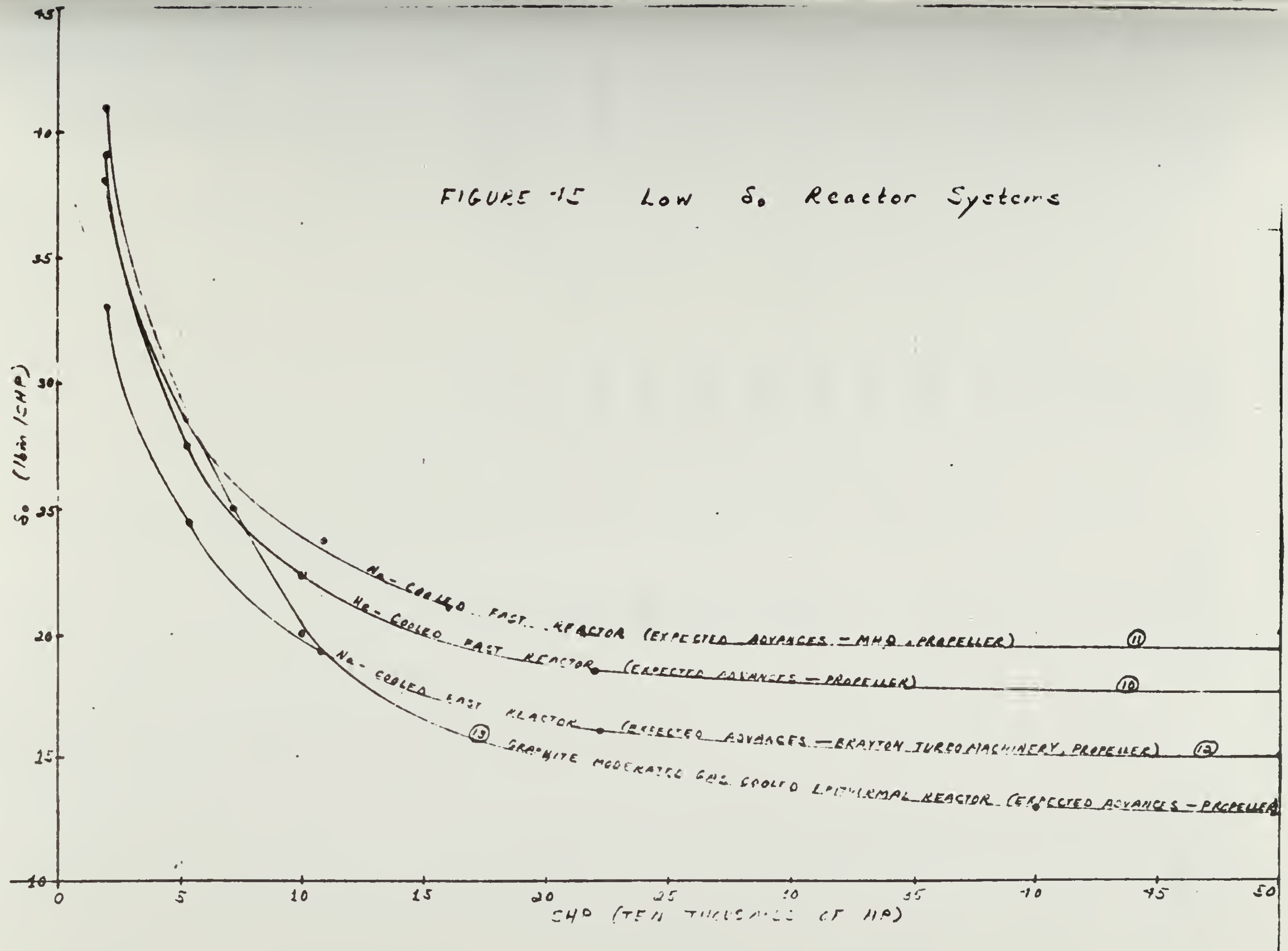


FIGURE 15 Low S_o Reactor Systems

TABLE 17

δ_e vs SHP SUMMARY FOR VARIOUS REACTOR SYSTEMS

SYSTEM	FIGURE	20,000 SHP	200,000 SHP
111 (NPWR Existing)	43-1	140	112
111 (CNSG Existing)	43-2	119	97
111 (NPWR Advanced)	43-3	114	92
111 (UNIMOD Existing)	43-4	92	72
111 (CNSG Advanced)	43-5	98	66
111 (UNIMOD Advanced)	43-6	63	38
411 (Existing Design)	44-7	78	54
411 (Advanced Design)	44-8	43	29
511 (Advanced Design)	44-9	80	36
251 (Advanced Design)	45-10	39	19
346 (Advanced Design)	45-11	38	20
351 (Advanced Design)	45-12	33	17
651 (Advanced Design)	45-13	41	15

The figures reveal that at the low end of the shaft horsepower spectrum, the overall specific propulsion weight δ_o increases due to the minimum practical sizes of components. At the high end of the shaft horsepower spectrum, δ_o decreases until it reaches some asymptotic limit beyond which point combinations of lower shaft horsepower plants must be utilized and the normalized weight essentially remains constant. Table 17 summarizes the results of the figures for existing systems and for expected advances utilizing superconducting generator electrical systems, planetary gears, and advanced collision systems. (See Appendix C for data on advanced collision systems).

In most cases, if a waterjet propulsion system is substituted for the subcavitating or supercavitating propeller transmission, only a few lbm/SHP difference results.

.7 Effects of Nuclear Plants on Ship Performance

To determine which nuclear plants might be feasible from a weight standpoint with various vehicles, the nuclear overall specific propulsion weight δ_o versus shaft horsepower figures were superimposed upon the δ_o limits versus shaft horsepower for the various ship types analyzed in Chapter . Figures 46 - 52 show these results.

.7.1 Ship Parameter Limitations

First, note should be made of the existing state of naval nuclear propulsion weight limits. For existing naval pressurized water reactors, as can be seen in Figure 46, for a 8500 ton conventional displacement ship, such as CGN25 the maximum sustained speed is limited to about 28 knots. To

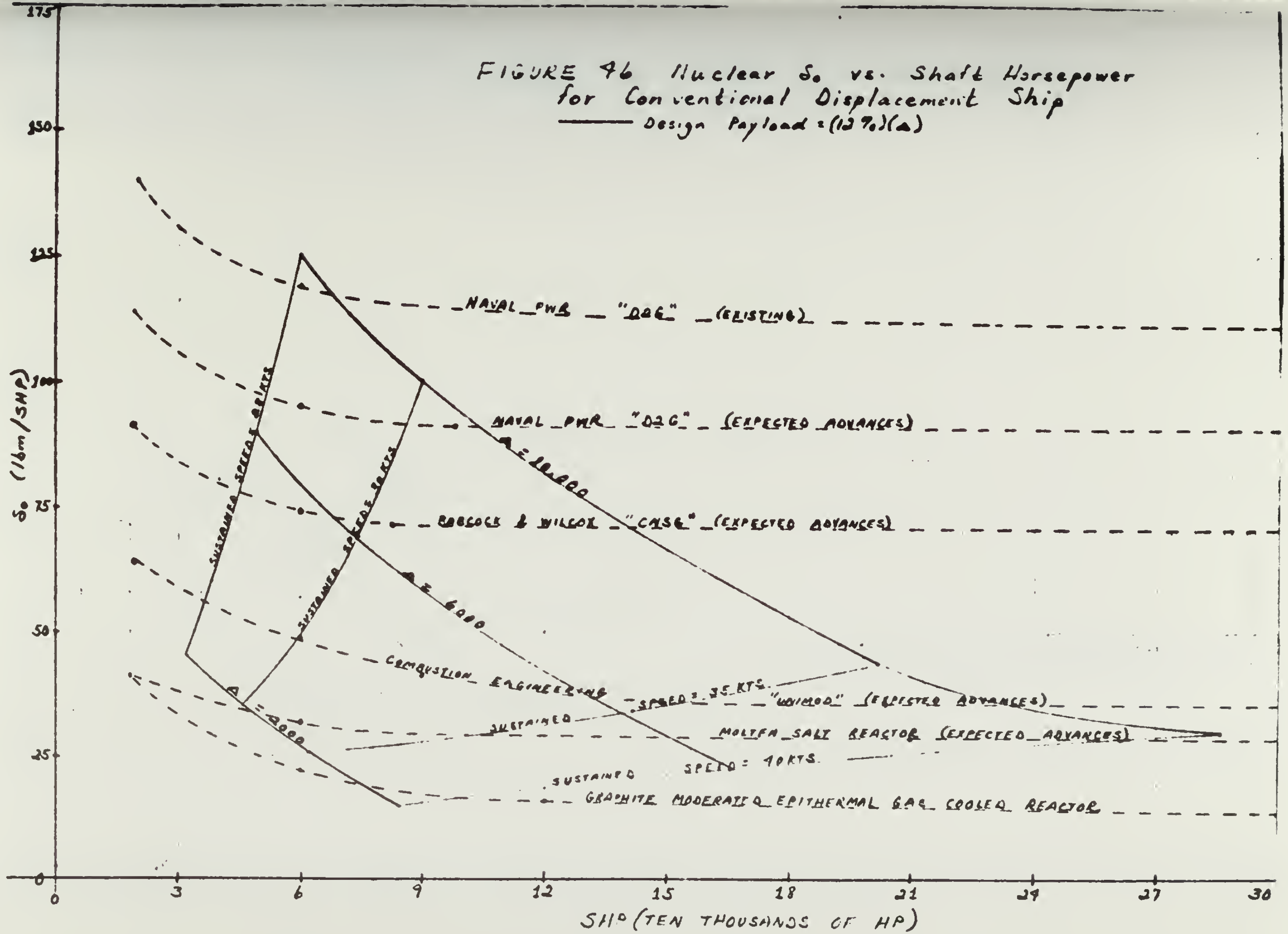


FIGURE 46 Nuclear S_o vs. Shaft Horsepower for Conventional Displacement Ship
—— Design Payload = (12%)(Δ)

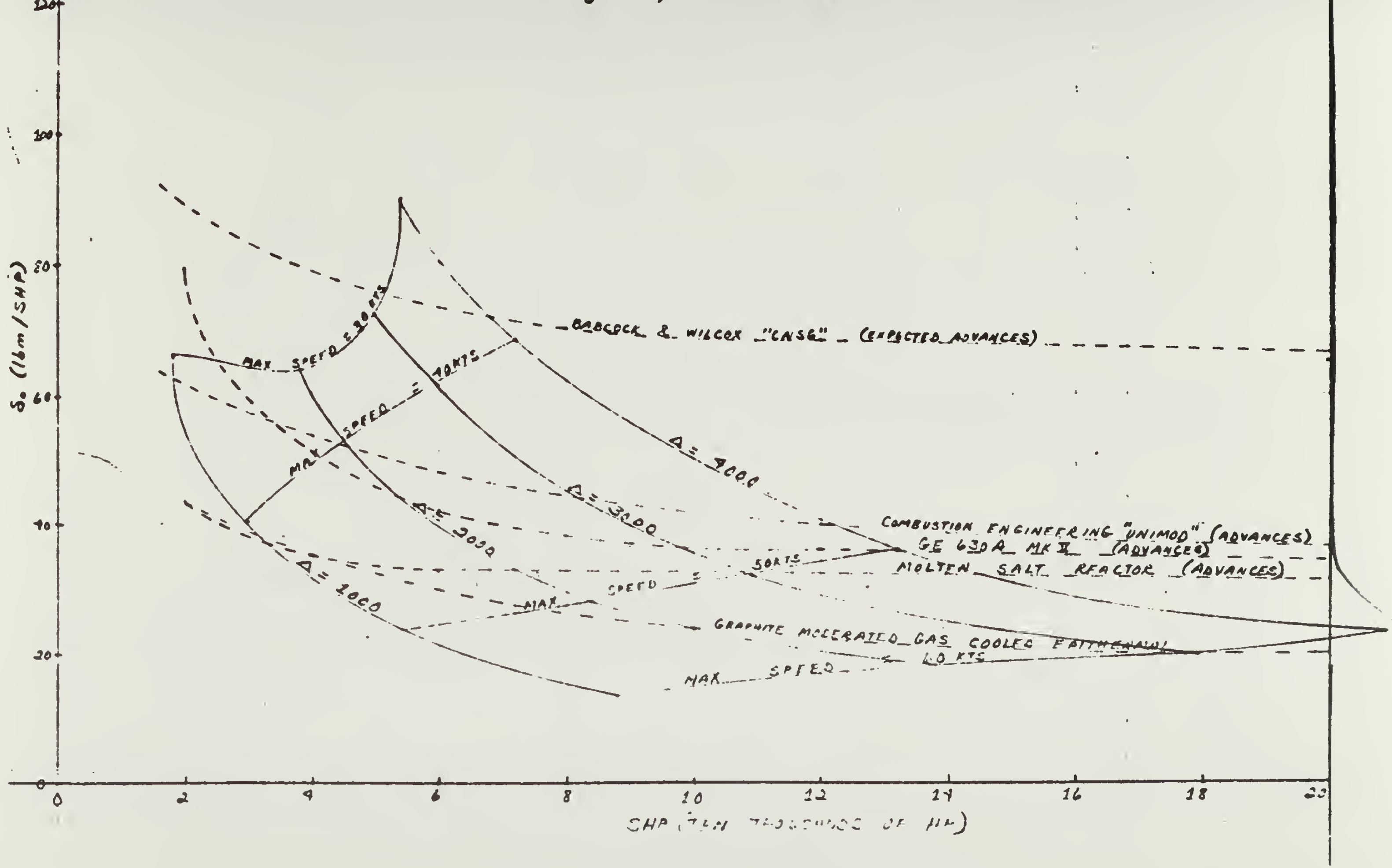


FIGURE 47 Nuclear δ_0 vs. Shaft Horsepower for High Performance Displacement Ship with Waterjets
------- Design Payload -(12%)(a)

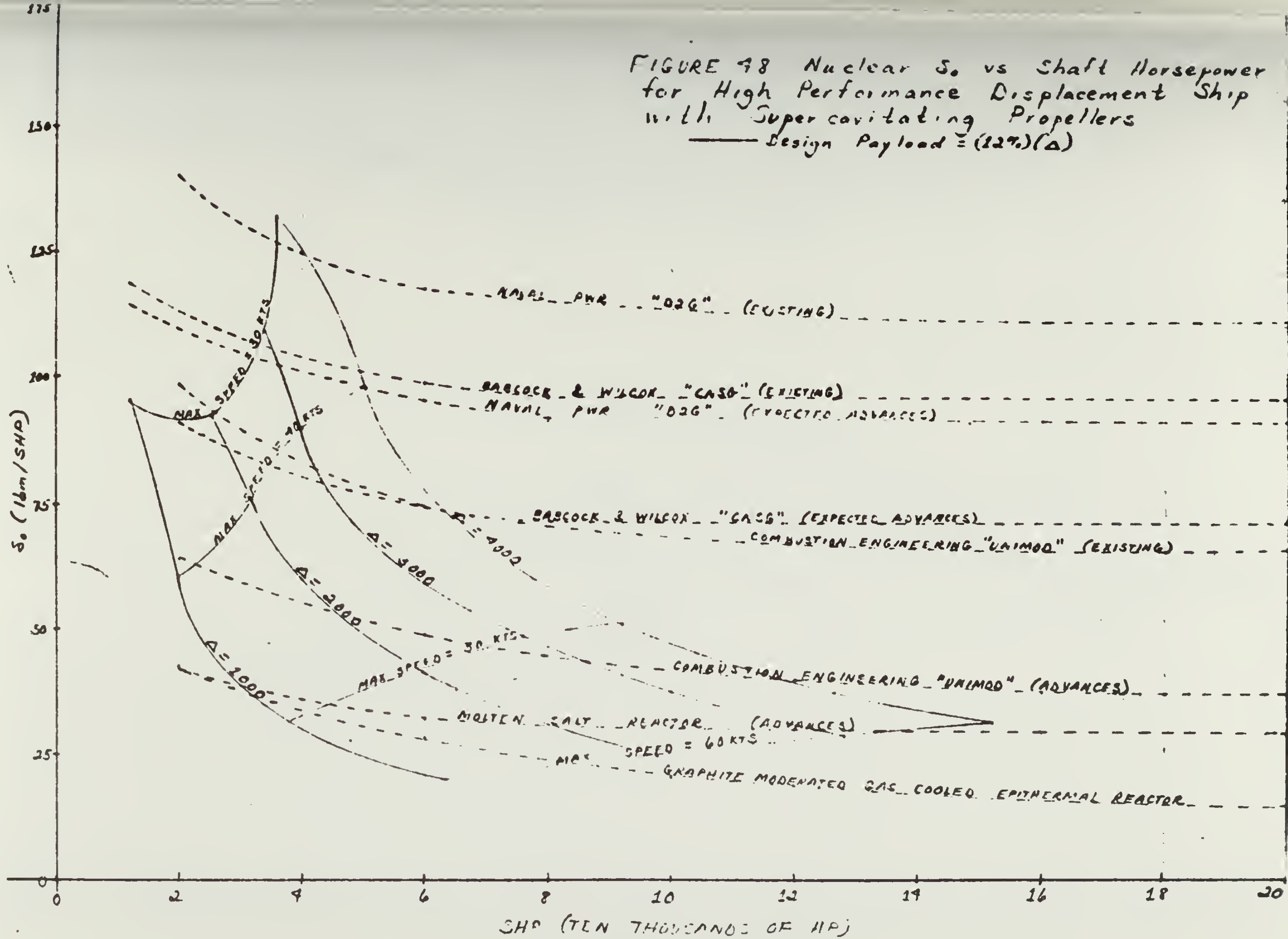


FIGURE 48 Nuclear S_o vs Shaft Horsepower for High Performance Displacement Ship with Supercavitating Propellers
—— Design Payload = (12%)(Δ)

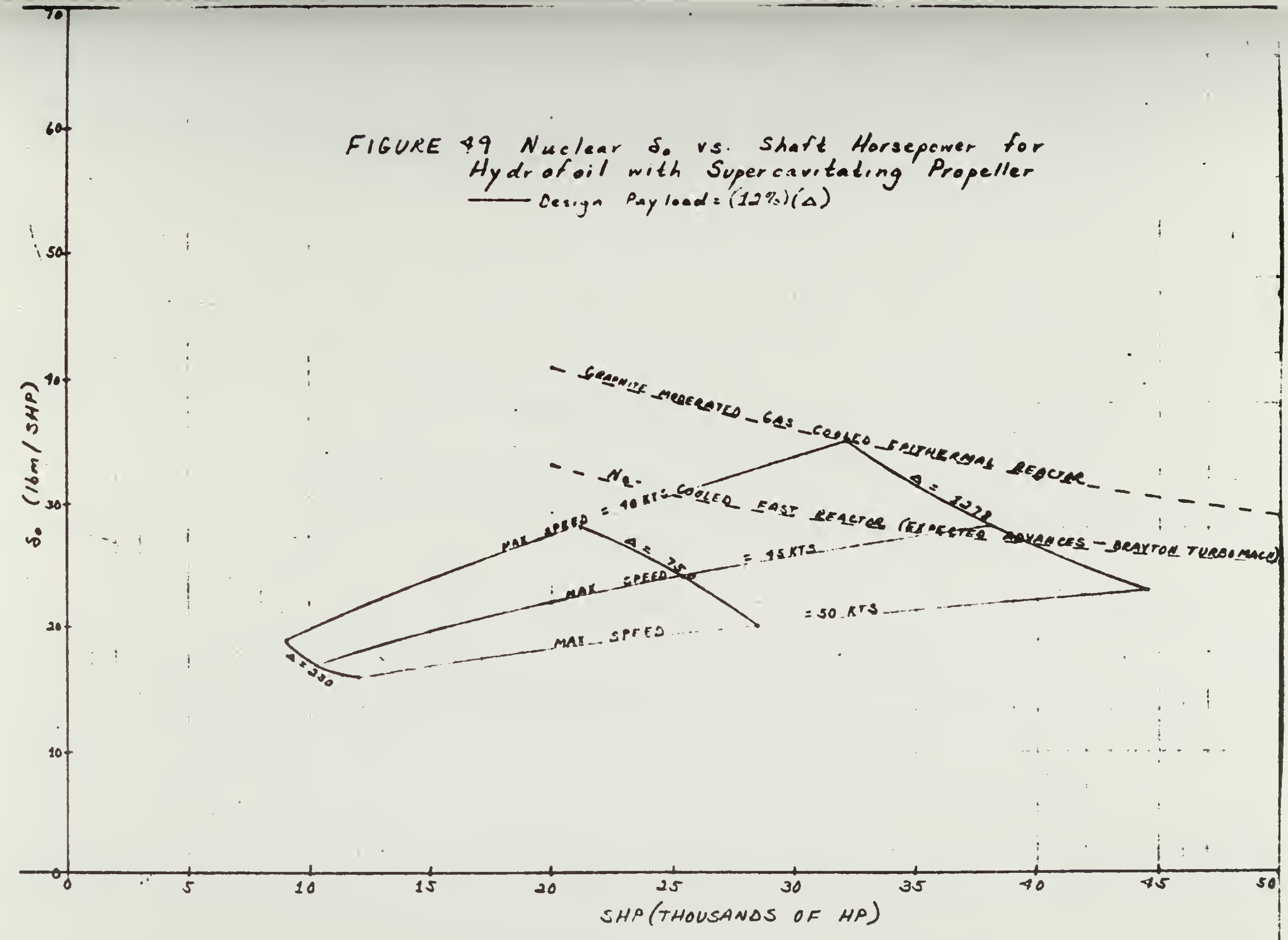


FIGURE 49 Nuclear δ_o vs. Shaft Horsepower for Hydrofoil with Supercavitating Propeller

—— Design Payload = (12%)(Δ)

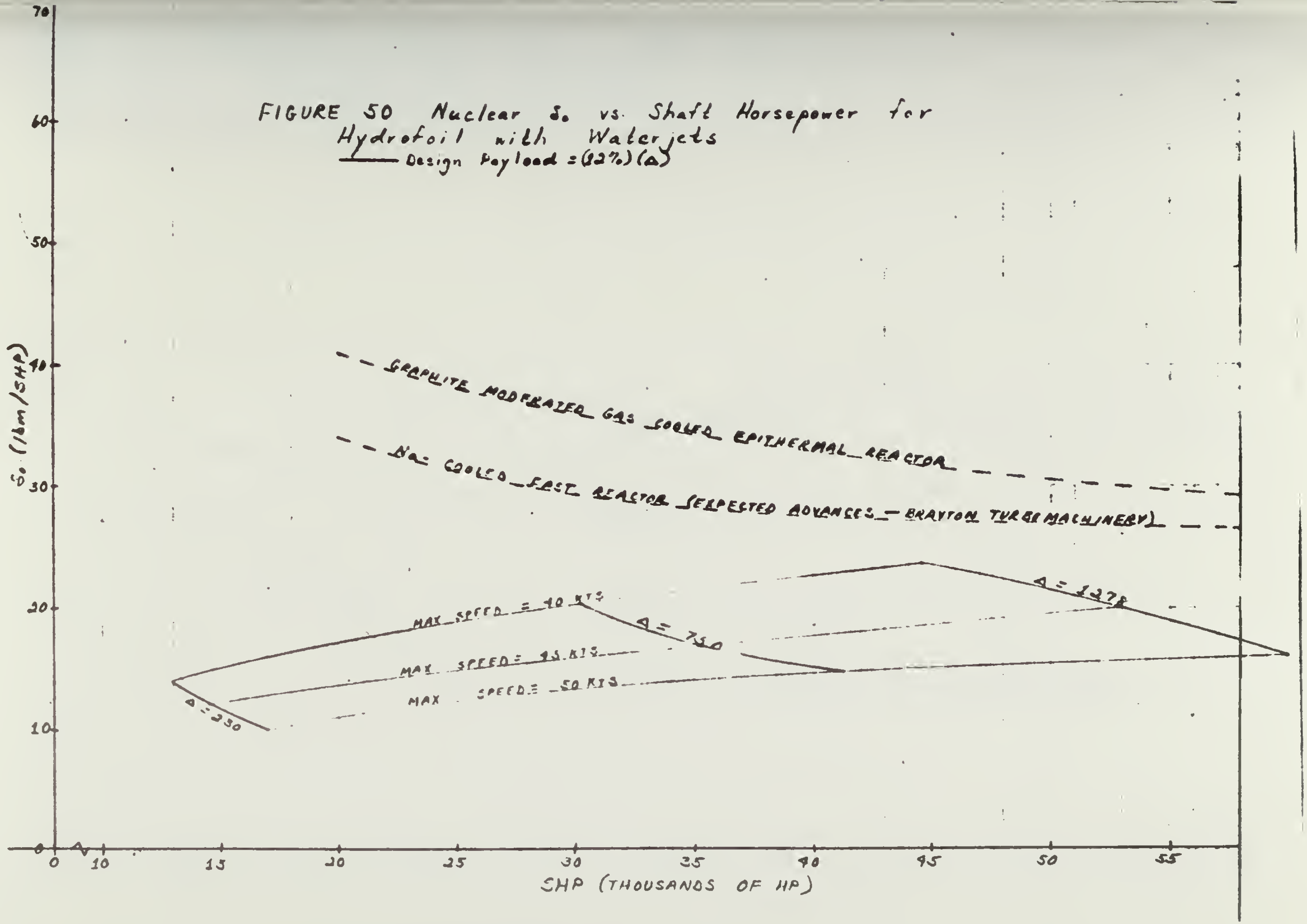


FIGURE 50 Nuclear δ_o vs. Shaft Horsepower for Hydrofoil with Waterjets

FIGURE 51 Nuclear δ_o vs Shaft Horsepower for Low l_c/b_c SFS with Supercavitating Propellers

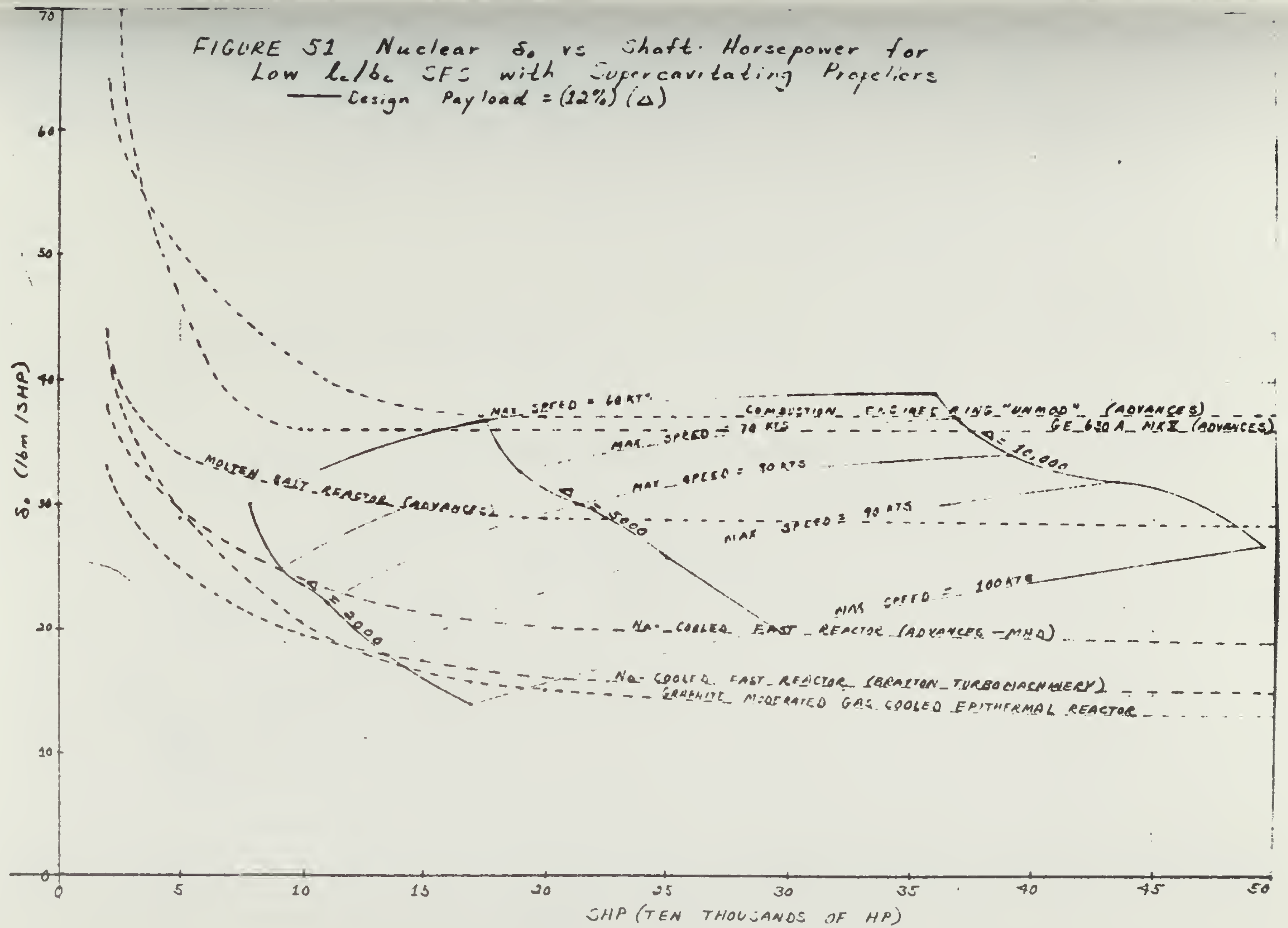
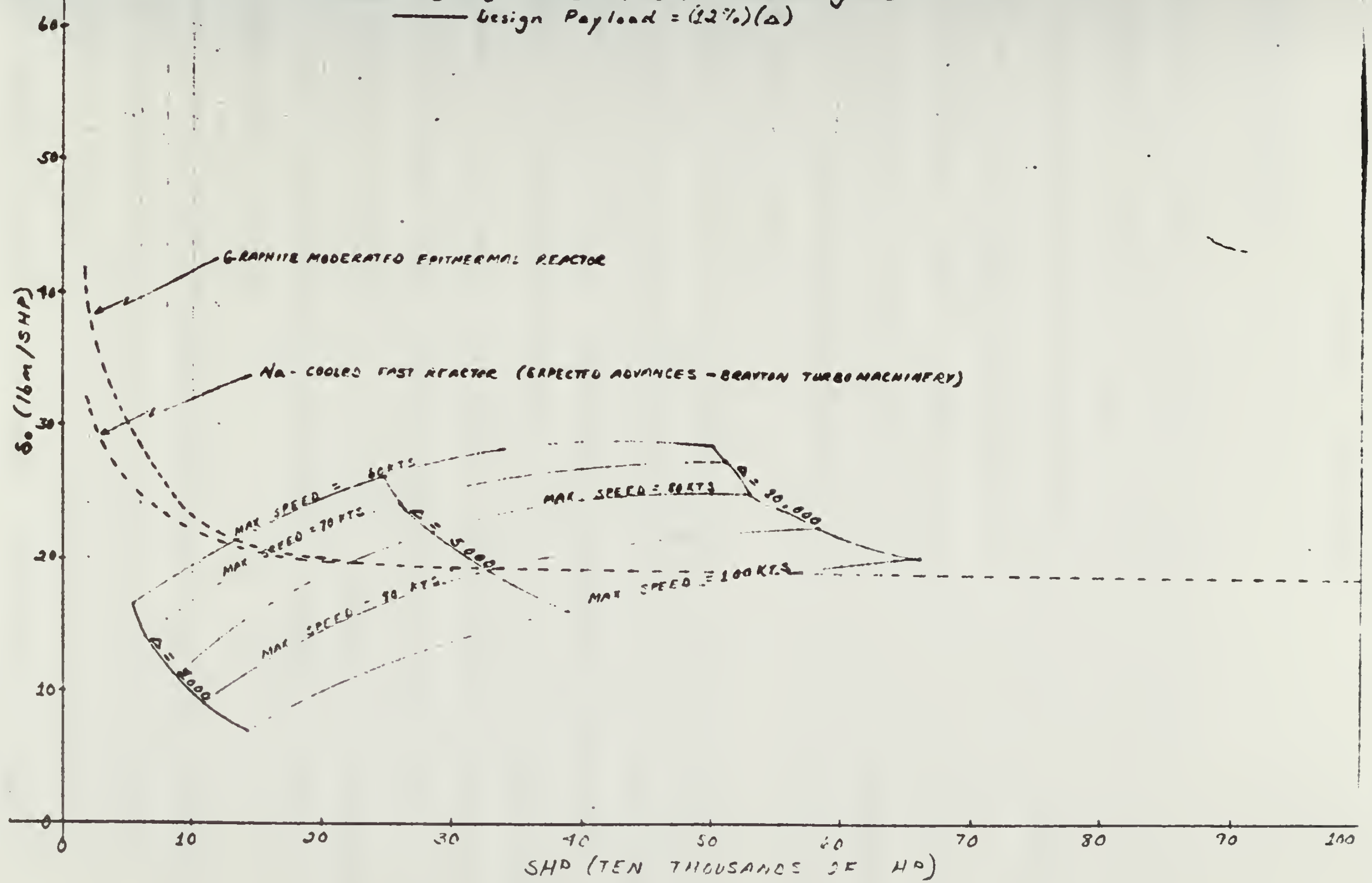


FIGURE 52 Nuclear δ_o vs Shaft Horsepower for Low ℓ_c/b_c SES with Waterjets



ncrease sustained speed to 28.5 knots, displacement would have to be ncreased to 10,000 tons to maintain a 12% payload.

.7.2 Potential Benefits

Now note will be made of possible benefits to be accrued if certain eactor systems were married with certain vehicles. To read the plots, for nstance in Figure 46 for the B & W "CNSG" (Expected Advances-Propeller), ote where the dark lines and dotted lines cross. Then draw a line arallel to the ordinate until it crosses the abscissa. This indicates hat for a 68,000 SHP B & W "CNSG" nuclear propulsion plant installed on 6000 ton conventional displacement ship, a 29.3 knots sustained speed can e attained for a 12% payload.

Although the current naval pressurized water reactor restricts ship imits, if advances to the plant such as planetary gears and superconducting enerators could be effected, it would allow as shown in Figure 46 decreasing isplacement to 6900 tons for 12% payload at 28 knots or increasing maximum ustained speed to 30.7 knots for a 8500 ton displacement ship with 12% ayload. If the integral type Combustion Engineering "UNIMOD" with xpected advances were substituted for the NPWR, (Figure 46) it would allow 3000 ton conventional displacement ship with 12% payload to attain a) knot maximum sustained speed.

However, direct cycle propulsion plants such as the He-cooled fast eactor, the indirect cycle Na-cooled fast reactor, and the gas cooled raphite moderated eipthermal reactor offer the greatest potential for ight-weight propulsion systems. For example, utilizing the graphite derated epithermal reactor would allow (Figure 46):

Increasing maximum sustained speed in a 2000 ton conventional displacement ship to 33 knots with a 12% payload or 40 knots in a 4000 ton conventional ship with 12% payload

Allow a full speed of 42 knots to be achieved for a 1278 ton hydrofoil with a 12% payload, employing a supercavitating propeller

Allow a full speed of 90 knots to be achieved for a 2000 ton low l_c/b_c SES with 12% payload, employing a supercavitating propeller

As can be seen in Figures 47 and 48, if the marriage between the point oads of reactor systems and the low density structural materials such as luminum could be effected, the reactor weight limitations of conventional isplacement ships could be lowered. In other words, high performance esign standards provide measures for making more weight available. No other pecific conclusions should be drawn from these figures since the HPDS is uch a developmental design at this time.

Among the high performance ships it can readily be seen that for resent hydrofoil limits (Figures 49 and 50), putting even the most advanced ight-weight reactor systems on board will be extremely difficult. The ES (Figures 51 and 52), on the other hand, appears to be a viable candidate n terms of weight restrictions with no degradation of expected payload or peed capabilities required. The only drawback to the SES reactor integration ay be due to cost limits since the SHP requirements translate into such igh costs. This may further bracket the maximum low l_c/b_cSES to 3000 tons, ince 80 knots requires 145,000 SHP with a supercavitating propeller system.

4.8 Summary of Nuclear Propulsion Weight Analysis

Through a systematic breakdown of potential light-weight nuclear propulsion systems into energy generation, conversion, and transmission groupings, possible nuclear propulsion systems were analyzed in terms of their overall specific propulsion weight and shaft horsepower. These plants were then examined to determine their potential in terms of payload weight fraction, speed, and displacement for the particular ship types.

Summarizing the overall specific propulsion weight δ_o for different propulsion systems at 20,000 shaft horsepower and δ_o for 200,000 shaft horsepower reveals the possible system approaches for achieving weight reductions for nuclear propulsion systems.

Heavy-Weight Reactor Systems

1. Naval pressurized water reactor system (NPWR):

   20,000 SHP $\quad \delta_o = 140$ lbm/SHP

   200,000 SHP $\quad \delta_o = 112$ lbm/SHP

2. NPWR with superconducting electrical generating system, planetary gears, and advanced collision system (expected advances);

   20,000 SHP $\quad \delta_o = 114$ lbm/SHP

   200,000 SHP $\quad \delta_o = 92$ lbm/SHP

3. Babcock & Wilcox "CNGS" with expected advances:

   20,000 SHP $\quad \delta_o = 92$ lbm/SHP

   200,000 SHP $\quad \delta_o = 72$ lbm/SHP

Intermediate-Weight Reactor Systems

1. Water moderated He-cooled reactor (GE630-A MK V) with expected advances:

20,000 SHP $\delta_o = 80$ lbm/SHP

200,000 SHP $\delta_o = 36$ lbm/SHP

2. Combustion Engineering "UNIMOD" with expected advances:

20,000 SHP $\delta_o = 63$ lbm/SHP

200,000 SHP $\delta_o = 38$ lbm/SHP

3. Molten salt reactor with expected advances:

20,000 SHP $\delta_o = 43$ lbm/SHP

200,000 SHP $\delta_o = 29$ lbm/SHP

Light-Weight Reactor Systems

1. Direct cycle He-cooled fast reactor with expected advances:

20,000 SHP $\delta_o = 39$ lbm/SHP

200,000 SHP $\delta_o = 19$ lbm/SHP

2. Indirect cycle Na-cooled fast reactor with MHD conversion:

20,000 SHP $\delta_o = 38$ lbm/SHP

200,000 SHP $\delta_o = 20$ lbm/SHP

3. Indirect cycle Na-cooled fast reactor with Brayton turbo-machinery conversion:

20,000 SHP $\delta_o = 33$ lbm/SHP

200,000 SHP $\delta_o = 17$ lbm/SHP

4. Graphite moderated gas cooled epithermal reactor

20,000 SHP $\delta_o = 41$ lbm/SHP

200,000 SHP $\delta_o = 15$ lbm/SHP

The heavy-weight reactor systems can only be installed on high displacement conventional ships. The intermediate-weight reactor systems can be installed on escort size conventional displacement ships, and on the surface effect ship. However, the high temperature, high reactor power density systems such as the

rect cycle He-cooled fast reactor, the indirect cycle Na-cooled fast actor, and the gas cooled graphite moderated epithermal reactor offer the eatest potential for light-weight nuclear propulsion systems on all high rformance ships except the hydrofoil.

Among the high performance ships, for the hydrofoil limits, putting en the most advanced light-weight nuclear systems on board will be tremely difficult. The low length-to-beam surface effect ship (SES) pears to be the most advantageous high performance ship in terms of weight, ace, and performance, although costs may ultimately limit the size of this ip.

CHAPTER 5

LIGHT-WEIGHT REACTOR TRADEOFFS

Before one is prejudiced to the conclusion that there should be "full peed ahead" with development of light-weight nuclear propulsion systems, an kamination must be made of the design compromises which are associated ith these reduced weight systems. It must be remembered, for instance, that ne aircraft derivative gas turbine had to be marinized to find a place in ne marine environment. This chapter will examine some of these tradeoffs, arine restrictions placed on reactor systems, and will outline a means by hich the feasibility and practicality of the proposed light-weight nuclear ropulsion plants can be determined.

.1 Naval Reactors Design Considerations

As opposed to the more common use of nuclear reactor systems in tationary electrical power plants, the marine nuclear propulsion system nposes many other design considerations due to the effects of the marine nvironment; the fact that the plant is mobile, thus possibly exposing reater populations; the fact that a ship is subject to collision; and the act that ship motions impose differing structural loadings as opposed to a tationary plant. Specifically, the marine reactor system must:

1. Consider watertight division, stability, fire protection, bilge pumping, fire extinguishing, electrical installations, steering gear, astern power, collision barriers (safety aspects of the particular ship design)
2. Provide for emergency propulsion and power

3. Provide a volumetrically restrained containment to consider the following:

    a. maximum credible pressure buildup within the containment due to an accident to the nuclear system

    b. maximum credible internal missile accident

    c. location as regards collision or grounding damage

    d. rupture of piping, ducts, or similar components connected to and passing through the containment

    e. external fires and explosions on board the ship

    f. fires within the containment

    g. sinking of the ship until salvage

    h. forces due to ship motion (increased loadings and effect on reactor characteristics)

    i. removal of decay heat in the event of loss of coolant circulation and provision for preventing the reactor core from melting through the containment

    j. leakage control and measurement of coolant leakage rate

4. Not adversely affect the bending moment of the ship(point load distribution considerations)

5. Take into account sea water corrosion, including corrosion of various structural elements of the ship: hull, bilge, foundations for the containment or other equipment, piping and ventilation ducts

7. Provide the following systems outside the containment (safety considerations):

   a. emergency power

   b. hydraulic power for hydraulic control systems

   c. control room including:

      i. reactor control

      ii. instrumentation

      iii. primary system control

      iv. main propulsion control

      v. electrical control

      vi. auxiliary control

      vii. radiation monitoring

      viii. containment closure control

8. Take into account weight, volume, and stability limitness of ships which bring dangers closer together

In addition, adapting the reactor system to a naval ship imposes even urther design considerations due to the fact that the reactor system is xposed to possible wartime conditions, and must be maintained on occasion way from logistic support in forward areas. In addition to the above onsiderations, the naval reactor must also:

1. Be maintainable away from logistic support for long periods (much longer operating periods than for a commercial nuclear ship transporting goods between two ports)

2. Provide containment which also considers the possibility of combat damage

3. Be able to make frequent power changes (naval ships must conduct anti-submarine chases, plane guard, etc., as opposed to the commercial nuclear ship which essentially can maintain a constant speed)

4. Be extremely reliable; otherwise, the stay time of the nuclear plant is negated (the mission endurance at top speed of the naval nuclear ship is <u>much</u> greater than the commercial nuclear ship)

5. Provide manual control backup/local remote for emergency/battle operation; provide redundant systems (a necessity for a naval ship to provide adequate damage control in battle)

us the design of a nuclear plant for naval ship propulsion deserves ose attention to many design features aside from weight considerations.

2 Reactor Figure-of-Merit

To judge the various proposed and existing reactor systems as a function specific propulsion weight, a figure-of-merit will be described that bodies the basic design philosophy of the naval nuclear propulsion system, clusive of weight considerations. The Figure-of-Merit is meant to be a "alue system" by which one judges the quality of a given design decision. r instance, with respect to a ship system, the following might form the sis for decisions on alternative solution:

- Minimum cost
- Operational excellence
- Availability
- Habitability

· Vulnerability and survivability

· Innovation

· Nonobsolescence

Figure 53 shows the breakup of the proposed Figure-of-Merit (FOM). e value of the FOM is made up of fifteen effectiveness elements which are ighted according to their relative importance. For instance, effectiveness ement "safety" would undoubtedly be weighted the highest. Then the gure-of-Merit becomes:

$$
\begin{aligned}
\text{FOM} = {} & W_1 \cdot (\text{safety}) + W_2 \cdot \left(\begin{matrix}\text{reliability/}\\ \text{ruggedness}\end{matrix}\right) + W_3 \cdot (\text{maintainability}) \\
& + W_4 \cdot \left(\begin{matrix}\text{availability/}\\ \text{propulsion readiness}\end{matrix}\right) + W_5 \cdot \left(\begin{matrix}\text{survivability/}\\ \text{vulnerability}\end{matrix}\right) \\
& + W_6 \cdot (\text{manning}) + W_7 \cdot (\text{costs}) + W_8 \cdot \left(\begin{matrix}\text{seaworthy}\\ \text{quality}\end{matrix}\right) \\
& + W_9 \cdot \left(\begin{matrix}\text{technological}\\ \text{nearness}\end{matrix}\right) + W_{10} \cdot \left(\begin{matrix}\text{political}\\ \text{acceptability}\end{matrix}\right) + W_{11} \cdot \left(\begin{matrix}\text{modernization}\\ \text{conversion}\end{matrix}\right) \\
& + W_{12} \cdot \left(\begin{matrix}\text{volume}\\ \text{minimization}\end{matrix}\right) + W_{13} \cdot \left(\begin{matrix}\text{standardization \&}\\ \text{producability}\end{matrix}\right) \\
& + W_{14} \cdot \left(\begin{matrix}\text{integrability \& compatability}\\ \text{with high performance ships}\end{matrix}\right) \\
& + W_{15} \cdot \left(\begin{matrix}\text{operational}\\ \text{performance}\end{matrix}\right)
\end{aligned}
\qquad (5.1)
$$

The effectiveness elements are further subdivided into effectiveness b-elements for further definition. A standard value X_i corresponding the accepted effectiveness sub-element norm, the "tried and true" naval essurized water reactor, is determined and an achieved value of the system Y_i be evaluated is also determined. These values should be determined as a sult of very extensive studies such as the Rasmussen WASH - 1400 (A3) study ich compares, for the instance, the probability of loss of coolant accidents various reactor systems. Therefore the final FOM now becomes:

$$
\begin{aligned}
\text{FOM} = \Big[& W_1 \sum_{i=1}^{12} \frac{Y_i}{X_i} + W_2 \frac{Y_{13}}{X_{13}} + W_3 \sum_{14}^{16} \frac{Y_i}{X_i} + W_4 \frac{Y_{17}}{X_{17}} \\
& + W_5 \sum_{18}^{21} \frac{Y_i}{X_i} + W_6 \sum_{22}^{23} \frac{Y_i}{X_i} + W_7 \sum_{24}^{25} \frac{Y_i}{X_i} + W_8 \sum_{26}^{27} \frac{Y_i}{X_i}
\end{aligned}
$$

$$+ W_9 \frac{Y_{28}}{X_{28}} + W_{10} \frac{Y_{29}}{X_{29}} + W_{11} \frac{Y_{30}}{X_{30}} + W_{12} \frac{Y_{31}}{X_{31}}$$

$$+ W_{13} \frac{Y_{32}}{X_{32}} + W_{14} \frac{Y_{33}}{X_{33}} + W_{15} \sum_{35}^{38} \frac{Y_i}{X_i} \qquad (5.2)$$

The values X_i and Y_i can be assigned in a most analytical manner but . should be pointed out that the weighting factors W_i and determination of e number of effectiveness sub-elements can be very subjective in nature. r instance, if W_i = 1000 were the maximum weighting factor and W_i = 1 e minimum weighting factor, the following ranking could be rationalized.

RANKING	EFFECTIVENESS ELEMENT	WEIGHTING FACTOR
1(To be traded off last)	Safety	W_1 = 1000
2	Reliability/ruggedness	W_2 = 980
3	Maintainability	W_3 = 950
4	Availability/propulsion readiness	W_4 = 920
5	Survivability/vulnerability	W_5 = 910
6	Operational performance	W_{15} = 900
7	Seaworthy quality	W_8 = 890
8	High Perf ship integrability	W_{14} = 700
9	Volume minimization	W_{12} = 690
10	Costs	W_7 = 500
11	Political acceptability	W_{10} = 250
12	Standardization & producability	W_{13} = 100
13	Manning	W_6 = 50
14	Technological risks	W_9 = 40
15(to be traded off first)	Modernization/Conversion	W_{11} = 10

FIGURE 53

Naval Reactor Figure-of-Merit

i	Effectiveness Element	Effectiveness Sub-Element	Definition	Standard Value	Achieved Value
V_1	Safety	Loss-of-Coolant	Minimize probability of LOCA Minimize effect and extent of LOCA	X_1	Y_1
		Flooding	Achieve $-\alpha_T$; Minimize reactivity power excursions, thermal stresses	X_2	Y_2
		Grounding	Provide emergency coolings prevent release of radioactivity	X_3	Y_3
		Internal Missile	Minimize probability of missile hazards resulting in radioactive rel.	X_4	Y_4
		Fire Hazards	Minimize probability of fire damage releasing radioactivity	X_5	Y_5
		Emergency Cooling	Provide for removal of reactor decay heat	X_6	Y_6
		Emerg Pwr & Propulsion	Provide for emerg pwr for vital rx services & emerg prop home	X_7	Y_7
		Radiation Shielding	Provide adequate shielding for normal berthing, maintenance, clad failures	X_8	Y_8
		Leakage & Makeup	Provide for makeup of coolant	X_9	Y_9
		Shut down Control	Provide for quick shutdown under all ship attitudes & plant conditions	X_{10}	Y_{10}
		Collision	Provide adequate collision barriers so no radioactivity released	X_{11}	Y_{11}
		Max Credible Pressure Build-Up	Provide adequate containment so pressure build-up releases no radioactivity	X_{12}	Y_{12}
V_2	Reliability/Ruggedness	Reliab/Rug of Equip Sys.	Maintain system reliability commensurate with rx endurance	X_{13}	Y_{13}
V_3	Maintainability	Overhaul/Refuel time	Minimize overhaul/refuel time	X_{14}	Y_{14}
		Accessibility	Provide adequate accessibility for at sea repairs	X_{15}	Y_{15}
		ILS Requirements	Provide adequate ILS to keep the rx at sea comm. with EFPH	X_{16}	Y_{16}
V_4	Availability (Propulsion Readiness)	Start-up & Shutdown Rates	Minimize start-up & shut-down times, bottom blows, etc.	X_{17}	Y_{17}
V_5	Survivability Vulnerability	Segregation	Segregation & seperation of vital functions	X_{18}	Y_{18}
		Shock & Blast Resist	Ability to withstand vibration, shock & blast damage/impact	X_{19}	Y_{19}
		Redundancy	Degree of redundancy in components, systems, etc.	X_{20}	Y_{20}
		DC, Stability Watertight Intg	Watertight flood-length ratio, righting arm/GM, damaged stability	X_{21}	Y_{21}
V_6	Manning	# of Crew	Number of engineering crew required	X_{22}	Y_{22}
		Skill level of crew	Skill, training required of engineering crew	X_{23}	Y_{23}

FIGURE 53 (cont.)

Naval Reactor Figure-of-Merit

V_i	Effectiveness Element	Effectiveness Sub-Element	Definition	Standard Value	Achieved Value
V_7	Costs	Acquisition	Developmental, design & production costs	X_{24}	Y_{24}
		Operational	Maintenance & overhaul, personnel & other operating costs	X_{25}	Y_{25}
V_8	Seaworthy Quality	Corrosion	Ability to withstand corrosion of foundations, piping, press. vessel, etc.	X_{26}	Y_{26}
		Motion Sensitivity	Sensitivity to six degrees of freedom (stresses, reactivity, etc.)	X_{27}	Y_{27}
V_9	Technological "Nearness"	Design & Developmental Risks	Estimate of risk associated with safe development & production of reactor system	X_{28}	Y_{28}
V_{10}	Political Acceptability	Political Acceptability	Degree of acceptability to the public	X_{29}	Y_{29}
V_{11}	Modernization/Conversion	Future Growth Rqmts Margins	Degree of margin in reactor system output	X_{30}	Y_{30}
V_{12}	Volume Minimization	Volume Minimization	Minimum volume required for reactor system	X_{31}	Y_{31}
V_{13}	Standardization & Producability	Standardization & Producability	Reduction of unique parts/ability to be easily produced	X_{32}	Y_{32}
V_{14}	Integrability & Compatability with High Perf. Ships	Load Distribution	Ability to be located at positions where bending moment accept.	X_{33}	Y_{33}
		System Integration	Ability to be integrated into the ship	X_{34}	Y_{34}
V_{15}	Operational Performance	Endurance EFPH	EFPH of core	X_{35}	Y_{35}
		Maneuvering Response	Load following characteristics, Ease of frequent maneuvering	X_{36}	Y_{36}
		Silencing	Degree of plant silencing achieved	X_{37}	Y_{37}
		Automation, Local/Manual Controls	Automation/Backup control, Ease of control	X_{38}	Y_{38}

Of course, a panel of experts might quantify this ranking quite differently than the author did above. Before any figure-of-merit is finally used, however, there should be a general agreement as to what are the priorities, say for a high performance ship application. By priorities, is meant ranking what is to be traded off first as opposed to what is to be traded off last.

5.3 Reduction of Reactor Systems Weight

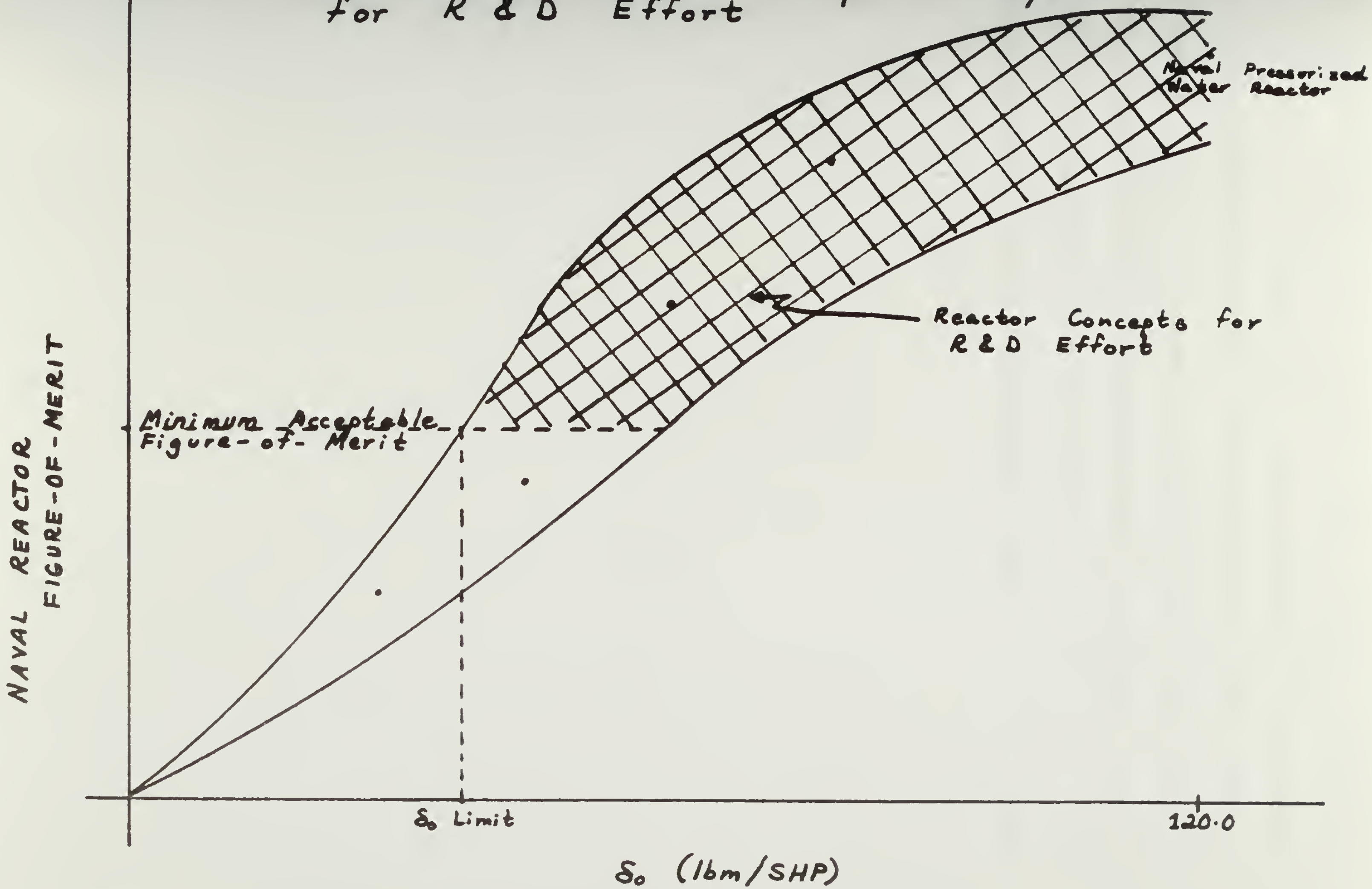
The proposed Figure-of-Merit or some facsimile of it could be used in an extensive study to compare the weight reducing reactor systems proposed in this study to assess the viability/feasibility of these concepts. Although such a study has not been completed, some estimative judgments have been made to demonstrate the type of curve that can be generated when the values of the FOM are plotted as a function of the overall specific propulsion weight δ_o. As shown in Figure 54, the probable trend would be that as δ_o decreased, the FOM would decrease. In other words, decreases in the nuclear propulsion plant weight would trade off many of the factors in the FOM such as safety, accessibility, etc.

Determination of a minimum acceptable value of the Figure-of-Merit would establish a δ_o limit for high performance ships. This δ_o limit would identify for each particular high performance ship the allowed displacement, maximum speed, and payload weight fraction. Furthermore, it would bracket the particular light weight nuclear propulsion systems to best invest Research and Development effort as shown in Figure 54.

5.4 Summary of Reactor Tradeoffs

Although many of the reactor concepts of Chapter 4 appear quite advantageous with respect to specific propulsion weight δ_o, low values of

FIGURE 54 Methodology for Bracketing Light Weight Nuclear Propulsion Systems for R & D Effort



δ_o may sacrifice vital reactor elements such as safety, reliability, and maintainability. An extensive study such as the WASH1400 study should be effected to determine the effect of decreasing δ_o on reactor design elements by comparing the various systems in a Nuclear Reactor Figure-of-Merit. If a lower limit of the Figure-of-Merit could be determined, then for the required overall specific propulsion weights the light-weight nuclear propulsion systems Research and Development area would be bracketed.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following overall conclusions have been obtained:

1. Fossil-fueled high performance ships such as the surface effect ship and hydrofoil require high specific powers and low specific propulsion weights. For fixed fuel weight fractions, endurance varies inversely with specific power, so high performance ships are therefore endurance limited, i.e. they have low "stay" capability.

2. Present naval pressurized water reactors require the following overall specific propulsion weights:

   (a) specific machinery weight = $\frac{\text{Group 2 Weight}}{\text{SHP}} = \delta_2$

   (b) collision/structural bulkheads and increases in propulsion foundations = $\frac{\text{Group 1' Weight}}{\text{SHP}} = \delta_{1'}$

   (c) increases in electrical machinery weight directly in support of nuclear plant = $\frac{\text{Group 3' Weight}}{\text{SHP}} = \delta_{3'}$

This translates into an overall specific propulsion weight $\delta_o = \delta_2 + \delta_{1'} + \delta_{3'} \approx 120$ lbm/SHP for installing a naval pressurized water reactor on board a typical ship.

3. For increasing ship displacements and decreasing maximum speeds, higher weight nuclear propulsion plants can be accomodated on board ships. For conventional displacement ships with a 12% weight fraction payload the following overall specific propulsion weight limits exist:

DISPLACEMENT (TONS)	MAX SUSTAINED SPEED (KTS)	δ_oALLOWED (lbm/SHP)
2,000	28	45
2,000	40	15
10,000	28	128
10,000	40	30

For a Series 64 monohull high performance displacement ship with a 2% weight fraction payload employing a supercavitating propeller:

DISPLACEMENT (TONS)	MAX SPEED (KTS)	δ_oALLOWED (lbm/SHP)
1,000	30	96
1,000	60	20
4,000	30	131
4,000	60	32

For a hydrofoil with 12% weight fraction payload employing a supercavitating propeller:

DISPLACEMENT (TONS)	MAX SPEED (KTS)	δ_oALLOWED (lbm/SHP)
230	40	19
230	50	14
1,278	40	35
1,278	50	23

For a low length-to-beam surface effect ship with 12% weight fraction payload employing a supercavitating propeller:

DISPLACEMENT (TONS)	MAX SPEED (KTS)	δ ALLOWED (lbm/SHP)
1,000	60	30
1,000	100	14
5,000	60	36
5,000	100	20

Furthermore, if a waterjet propulsion system is substituted for the supercavitating propellers, the reduction in propulsive coefficient increases the required shaft horsepower to such an extent that the overall specific propulsion weight must be lowered from 6 to 30 lbm/SHP depending on ship type, displacement and speed.

4. Utilization of high performance design criteria in the non-propulsion features of the ship as embodied in the design of hydrofoils provides weight savings that allow for greater specific propulsion weight nuclear plants to be installed.

5. The current naval pressurized water loop reactor weight-limits restrict conventional displacement ships to a maximum sustained speed of 28 knots for a 8500 ton displacement with 12% weight fraction payload. Advances to this plant such as planetary gears and superconducting generators would allow decreasing displacement to about 6900 tons for 12% payload at 28 knots or increasing maximum sustained speed to 30.7 knots for 8500 ton displacement ship with 12% payload. If the integral type Combustion Engineering "UNIMOD" reactor with planetary gears and superconducting generators were

substituted for the naval pressurized water reactor, it would allow a 3000 ton conventional displacement ship with 12% payload to attain a 30 knot maximum sustained speed.

6. Summarizing the overall specific propulsion weight δ_o for different propulsion systems at 20,000 shaft horsepower and δ_o for 200,000 shaft horsepower reveals the possible system approaches for achieving weight reductions in nuclear propulsion systems:

<u>Heavy-Weight Reactor Systems</u>

1. Naval pressurized water reactor system (NPWR):

20,000 SHP	δ_o = 140 lbm/SHP
200,000 SHP	δ_o = 112 lbm/SHP

2. NPWR with supercavitating electrical generating system, planetary gears, an advanced collision systems (expected advances):

20,000 SHP	δ_o = 114 lbm/SHP
200,000 SHP	δ_o = 92 lbm/SHP

3. Babcock & Wilcox "CNSG" with expected advances:

20,000 SHP	δ_o = 92 lbm/SHP
200,000 SHP	δ_o = 72 lbm/SHP

<u>Intermediate-Weight Reactor Systems</u>

1. Water moderated He -cooled reactor (GE 630-A MK V) with expected advances:

20,000 SHP	δ_o = 80 lbm/SHP
200,000 SHP	δ_o = 36 lbm/SHP

2. Combustion Engineering "UNIMOD" with expected advances:

20,000 SHP	δ_o = 63 lbm/SHP
200,000 SHP	δ_o = 38 lbm/SHP

3. Molten salt reactor with expected advances:

20,000 SHP	δ_o = 43 lbm/SHP
200,000 SHP	δ_o = 29 lbm/SHP

<u>Light-Weight Reactor Systems</u>

1. Direct cycle He-cooled fast reactor with expected advances:

20,000 SHP	δ_o = 39 lbm/SHP
200,000 SHP	δ_o = 19 lbm/SHP

2. Indirect cycle Na-cooled fast reactor with MHD conversion:

20,000 SHP	δ_o = 38 lbm/SHP
200,000	δ_o = 20 lbm/SHP

3. Indirect cycle Na-cooled fast reactor with Brayton turbomachinery conversion:

20,000 SHP	δ_o = 33 lbm/SHP
200,000 SHP	δ_o = 17 lbm/SHP

4. Graphite moderated gas cooled epithermal reactor:

20,000 SHP	δ_o = 41 lbm/SHP
200,000 SHP	δ_o = 15 lbm/SHP

7. The heavy weight reactor systems can only be installed on high displacement conventional ships. The intermediate-weight reactor systems can be installed on escort size conventional displacement ships and on the surface effect ship. However, the high temperature, high reactor power density systems such as the direct cycle He-cooled fast reactor, the indirect

cycle Na-cooled fast reactor, and the gas cooled graphite moderated epithermal reactor offer the greatest potential for light-weight nuclear propulsion systems on all high performance ships except the hydrofoil.

Among the high performance ships, for the hydrofoil δ_o limits, putting even the most advanced light-weight nuclear systems on board will be extremely difficult. The low length-to-beam surface effect ship (SES) appears to be the most advantageous high performance ship in terms of weight, space, and performance.

8. Although many systems such as the gas cooled graphite epithermal reactor appear feasible from a δ_o standpoint, for use on all high performance ships, the overall reactor safety, maintainability, reliability, etc., so important to a naval reactor are suspect. An extensive comparative study of all the proposed light-weight nuclear propulsion systems should be effected to determine the possible deleterious tradeoffs made for weight in terms of safety, reliability, maintainability, accessibility, etc.

62 Recommended Future Investigations

Based on the results of this study the author was unable to conclude if nuclear propulsion could be applied to high performance ships such as surface effect ships and hydrofoils and to small conventional displacement ships. Additional research would have to be contributed to answer many questions which have arisen as a result of this study. The following recommendations for

uture investigations relating to light-weight nuclear propulsion applications o high performance ships are made:

1. Complete a detailed study of collision barriers for possible light-weight nuclear propulsion systems.
2. Complete a study of the problems and effects of various weight nuclear propulsion plants on foundation weight, e.g. the marriage of nuclear reactor point loadings on aluminum structures found in high performance ships.
3. Complete a study of the volume and stability effects of nuclear propulsion systems on high performance ships.
4. Complete a detailed design integration of various proposed light-weight nuclear propulsion plants into high performance ships.
5. Complete a detailed study of the more promising light-weight nuclear propulsion plant concepts to determine performance in such areas as reliability, maintainability, availability, safety, etc. Then conduct a probabilistic fault-tree analysis comparing the light-weight nuclear propulsion plants to determine their viability/feasibility.
6. Complete a cost/performance estimate of light-weight nuclear propulsion systems and high performance ship integration to determine if a small, high performance ship would be more cost beneficial than more conventional nuclear propulsion ships.

REFERENCES

1 Aroner, R. and Hubbard, R. M., "DEH, A High Endurance Escort Hydrofoil for the Fleet," Paper #74-311, AIAA/SNAME Advanced Marine Vehicles Conference, San Diego, Calif., February,1974.

2 Adler, Ronald E., "Mission Suitability of Naval Hydrofoils," Professional Summer at M.I.T., 1975.

3 Atomic Energy Commission, Reactor Safety Study --- An Assessment of Accident Risks in U. S. Commercial Power Plants,USAEC 1400 (Draft), Washington, D. C., August, 1974.

1 Beving, Duane U., Optimization of Parameters for a Nuclear Gas Turbine Plants, Department of Ocean Engineering Thesis, M.I.T., May, 1962.

2 Bauman, James Robert, Lt,. USN, Analysis of Past, Present and Future Applications of Nuclear Power for Propulsion of Marine Vehicles, Ocean Engineering Thesis, May, 1972.

3 Bebar, M. R., Hydrofoil Ocean Combatant Concept Design Baseline Report, NavSec Report 6114 - 75 - 20, (CONF.), April, 1975.

4 Bement, Arden, 22.75J Course Notes, Spring, 1975.

5 Beideweser, Donald W. et al., "The Path Ahead for Nuclear Merchant Ships," SNAME Annual Meeting, November, 1966.

6 Bukalov, V. M., et al., Atomic Powered Submarine Design, National Technical Information Service, December, 1967.

1 Conolly, A. C., "Prospects for Very-High-Speed Hydrofoils, "Marine Technology, Volume 12, No. 4, (October, 1975).

2 Cuthbert, J., "Technology of SES -- Propulsion," Professional Summer at M.I.T., Advanced Marine Vehicles, 10 July, 1975.

3 Chaplin, H., "Wing in Ground Effect (WIG), " M.I.T. Advanced Marine Vehicles Professional Summer Program, 7 July, 1975.

4 Crewe, P. R., "Air Cushion Vehicle Skirt System," M.I.T. Advanced Marine Vehicle Professional Summer, 9 July, 1975.

5 Comyn, M.I., A Nuclear Plant Proposal for the Arctic Bulk Carrier, Ocean Engineering Thesis, May, 1972.

1 Davis, S., "Technology of SES -- Hydrodynamics of the Hull and Response in Waves," Advanced Marine Vehicles, Professional Summer at M. I. T., 10 July, 1975.

D2 Dewey, W. A., "Conceptual Design for Surface Effect Ship (SES) in Coast Guard Applications," NSRDC Tech Note AL-311, September, 1973.

D3 Decker, J. L., "High-Speed Marine Vehicles - A Design Outlook," Hovering Craft and Hydrofoils, Volume 12, No. 3, December, 1972.

E1 Eggington, Wilfred J. and Nat Kobitz, "The Domain of the Surface-Effect-Ship," SNAME New York, N. Y. Annual Meeting, November 13 - 15, 1975.

E2 El Wakil, M. M., Nuclear Energy Conversion, International Textbooks Co., 1971.

E3 Etherington, Harold (Edit), Nuclear Engineering Handbook, McGraw-Hill Book Company, 1958.

E4 Ebber, Harry S., "Biological Aspects of Nuclear Propulsion," SNAME, Spring Meeting, April, 1961.

F1 Fee, J., LCDR, USN, "SES - Unique Aspects and Tradeoffs,"(CONF.), Professional Summer at M.I.T. Advanced Marine Vehicles, 10 July, 1975.

F2 Friedman, Ben., "Propulsion - Power Generation Sources, Power Conversion, Power Transmission, ONR., 1975.

F3 Forrest, C. L., "Test and Evaluation of the SES - 100B," AIAA Paper #74 - 317.

F4 Foster, A. R., and Wright, R. L., Basic Nuclear Engineering, Allyn and Bacon, Inc., 1973.

F5 Fahy, Thomas E., The Impact of High Performance Technology on Naval Ship Design, Ocean Engineering Masters Thesis, May, 1976.

G1 Goldsmith, Marc Warren, Evaluation of a Gas-Cooled Fast Breeder Reactor for Ship Propulsion, Department of Nuclear Engineering Thesis, M.I.T., August, 1972.

G2 Grostick, John L., A Comparative Analysis of Naval Hydrofoil and Displacement Ship Design, Department of Ocean Engineering Thesis, M.I.T., June, 1975.

G3 Glasstone and A. Sesonske, Nuclear Reactor Engineering, Van Nostrand, 1963.

G4 Golden, D., R. B. Knapp, and W. Idsinga, Conceptual Design of High Speed Escort, Course 13.46 M.I.T. Design Project, May, 1975.

G5 Goldberg, L. L. and R. G. Tucker, "Current Status of U. S. Naval Stability and Buoyancy Criteria for Advanced Marine Vehicles," 11th Annual Symposium of the Association of Senior Engineers, 1975.

G6 Gathy, B. S., "A Marine Nuclear Power Plant Design Utilizing the Direct Brayton Cycle," ASME Paper 70 - GT - 3.

G7 Golay, Michael, 22.311 Course Notes, Spring, 1975.

G8 Geyer, L. A., and G. J. Wennagel, "A Feasibility Study of Hydrofoil Seacfart," <u>SNAME Transactions</u>, 1959.

G9 Graham, Clark, 13.22 Class Notes, 1974.

G10 <u>Guide for the Classification of Merchant Ships</u>, American Bureau of of Shipping, 1962.

G11 <u>General Design Criteria for Nuclear Merchant Ships</u>, Rev. 2, Babcock & Wilcox TRG - 73 - 57, 1973.

G12 Gilbert, W. E., "Empirical Design of Peripheral Collision Protection Structure for the Arctic Surface Effect Vehicle," NSRDC Report 4232.

G13 Greene, David L., <u>Analysis of a Marine Propulsion System Incorporating Superconducting Electrical Machinery</u>, Ocean Engineering PHD Thesis, January, 1970.

G14 Giannotti, Julio G., <u>A Review of Propulsors Likely to Be Available for the Advanced Naval Vehicles in the 1980 - 2000 Time Period</u>, Payne Inc., 1976.

H1 Hoerner, S. F., "Consideration of Size-Speed-Power in Hydrofoil Craft," Gibbs and Cox Inc., Report 14131/S1/1 (1 - 502), November, 1958.

H2 Heller, S. R. and Clark, D. J., "The Outlook for Lighter Structures in High Performance Marine Vehicles," <u>Marine Technology</u>, Vol. 11, No. 4, October, 1974.

H3 Harrington, Roy L., <u>Marine Engineering</u>, SNAME, New York, N.Y., 1971.

H4 Henry, A. F., Course Notes, 22.211, 22.212, 1974 - 1975.

J1 Jewel, David A., "Hybrid Fluid-Media Vehicles," Naval Ship Research and Development Center Report No. 4247, August, 1973.

J2 Joint Committee on Atomic Energy, ANP Program, 85th and 86th Congress (1958 - 1959), Volume 22.

J3 Jaeger, Thomas, <u>Principles of Radiation Protection Engineering</u>, McGraw-Hill Book Company, 1965.

K1 Kramer, A. W., <u>Boiling Water Reactors</u>, Addison Wesley Publishing Co., 1958.

K2 Kramer, A. W., <u>Nuclear Propulsion for Merchant Ships</u>, USAEC, USGPO, 1962.

L1 Lacey, R., "Design Criteria and Practices," Professional Summer at M.I.T., Surface Ship Design, 1975.

L2 Lancaster, J. H., "Some Observations of Present and Future Marine Power Plants," SNAME #16, P116 - 3. 1968.

L3 Lamarsh, J. R., Nuclear Reactor Theory, Addison Wesley Publishing Co., Inc., 1966.

L4 Leopold, Reuven, and Wolfgang Reuter, "Three Winning Designs - FDL, LHA, DD-963: Method and Selected Features," SNAME Annual Meeting Paper #5, November 11 - 12, 1971.

M1 Mandel, P., "A Comparative Evaluation of Naval Ship Types," SNAME Transactions Volume 70, 1962.

M2 Miller, R. T., Long, C. L., and Reitz, S., Naval Engineer's Journal, Vol. 84, No. 6., December, 1972.

M3 Moore, John E., Janes Fighting Ships 1974 - 1975, McDonald and Co., (Publishers) Ltd., London, England, 1974.

M4 Mandel, P., Water, Air, and Interface Vehicles, National Science Foundation Sea Grant Project GH - 1, Massachusetts Institute of Technology, M.I.T. Press, Cambridge, Massachusetts, 1969.

M5 Mandel, P., "Interim Report of Mathematical Model of Destroyer-Cruiser Design Problem, Institute for Naval Studies Research Contribution No. 1," (CONF.), Center for Naval Analyses, Washington, 25, D.C.

M6 Meyer, John R., Jr., "Calm-Water Speed-Power of Hybrid Ship Research and Development Center, Advanced Concepts Office, June, 1975.

M7 Mantle, P. J., "Air Cushion Lecture Structural System," Professional Summer at M.I.T., 9 July, 1975.

P1 Perkins, W. F., Jr., "Discussion Notes for a Review of Progress in Design of Large SES," Marine Technology, Volume 12, No. - 3, (July, 1975).

P2 Palmer, Irwin, "Hydrofoil Technology Assessment," Professional Summer at M.I.T., 1975 .

P3 Proceedings of the Symposium on Nuclear Ship Propulsion (40 papers), IAEA Taormina, Taormina, Italy, November 14 - 18, 1960.

P4 Proceedings of the Symposium on Nuclear Ships Vol. I/II (54 papers) IAEA Hamburg, Germany, May 10 - 15, 1971.

5 Petrick, M., W. E. Amend, E. S. Pierson, and C. Hsu, "Investigation of Liquid-Metal Magnetohydrodynamic Power Systems," ONR Report ANL/ETD - 70 - 12, December, 1970.

6 Potter, E. B., and Chester W. Nimitz - Editors, Sea Power, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1960.

7 Payne, Inc., A Review of Power Plants Likely to Be Available for Advanced Naval Vehicles in the 1980 - 2000 Time Period, March, 1976.

11 Rickover, Hyman G., "Nuclear Power for Surface Warships," Testimony Before Congressional Committee, 1963.

12 Roberts, Ralph, Report of Workshop on Light-Weight Nuclear Power Plants (22 - 25 October, 1974), Navy Department, Office of Naval Research, January 14, 1975.

13 Riddell, F. R., Survey of Advanced Propulsion Systems for Surface Vehicles, (Paper P - 1073), Institute for Defense Analysis Science and Technology Division, January, 1975.

4 Ray, C. T., "Intrinsic Hydrofoil Characteristics," Professional Summer at M.I.T., 1975.

5 Rockwell, T., Reactor Shielding Design Manual, USAEC, Van Nostrand, 1956.

6 Rosenblatt & Sons, Inc., The Surface Effect Ship - Advanced Design and Technology, New York.

7 Read, William. L., Adm., USN, "Advanced Naval Vehicles - Technology Responsive to Need," Address to Advanced Marine Vehicles Seminar at Professional Summer at M.I.T., July, 1975.

8 Reade, John M., IV, Design Criteria for Nuclear Powered Merchant Ships, Ocean Engineering Thesis, May 23, 1973.

9 Rosehnow, Warren M. and Harry Y. Choi, Heat, Mass, and Momentum Transfer, Prentice Hall Inc., Englewood Cliffs, N.J., 1961.

10 Rosenblatt, M. & Son, Inc., The Surface Effect Ship Advanced Design and Technology, New York, N.Y.

11 Rickover, H.G., RADM, USN, Capt. J.M. Dunford, Theodore Rockwell, III, LCDR, W.C. Barnes, and Milton Shaw, "Some Problems in the Application of Nuclear Propulsion to Naval Vessels," SNAME Transactions, 1957.

1 Schaffer, R. L., Deepwater Escort Hydrofoil (DEH) Ship Five Conceptual Designs (CONF.), NAVSEC Report 6114 - 74 - 16, February, 1974.

2 Schultz, M. A., Control of Nuclear Reactors and Power Plants, McGraw-Hill, 1961.

3 Soland, J., M. Goodwin, R. Marcolini, and P. Hagstrom, Conceptual Design of U.S.C.G. Patrol Vessel - WPV, Course 13.46 M.I.T. Design Project, May, 1975.

4 Sorkin, G., C. H. Pohler, A. B. Stavovy, and F. F. Borriello,"General Considerations Regarding the Structural Design of High Performance Ships," Marine Technology, Volume 12, No. 3, (July, 1975).

5 Sarchin, Theodore H., "Development of the SWATH Ship for Navy Application," Advanced Ship Studies Section Advanced Technology Branch Naval Ship Engineering Center, February, 1974.

6 Schuler, James L., "A Case for Nonconventional Surface Ship Design," Advanced Technology Systems Division, Naval Sea Systems Command, Presented at NATO IEG - 6 Meeting, 19 June, 1975.

7 Seng, William R., "Low Specific Weight Power Plants," Advanced Propulsion Concepts Technical Working Group Meeting, 20 and 21 October, 1975.

8 Savitsky, Daniel, John K. Roper, Lawrence Benen, "Hydrodynamic Development of a High Speed Planing Hull for Rough Water," Ninth Symposium Naval Hydrodynamics, Volume 1, Office of Naval Research ACR 203.

9 Soland, Jim, and Randolph M. Brooks, 13.22 Design Project, 1974.

10 Safety Considerations for Nuclear Power Plants on Merchant Ships, SNAME T & R Bulletin No. 3 - 18, 1965.

1 Taggart, R., E. D. Hoyt, and S. Hawkins,"Performance Criteria for Hydrofoil Craft," April, 1971.

1 U.S. Atomic Energy Commission Title 10, Code of Federal Regulations.

2 U.S. Coast Guard Title 46, Code of Federal Regulations.

1 Vann, H. E., M. L. Weiss, and B. Wolfe, "Shielding Aspects of Nuclear Power Plants for Marine Propulsion," SNAME Transactions, 1958.

1 Wilson, W. B., and P. V. Lombardi, "Interim Procedure for the Calculation of High Performance Ship Endurance Fuel Requirements," Naval Ship Engineering Center, January, 1974.

2 Westcott, G. D.,"A Review of the U. S. Navy's SES-100A Program," AIAA Paper #74 - 316.

West, George L. et al., "Some Aspects of Nuclear Safety and Ship Design," SNAME Annual Meeting, November, 1967.

Yeh, Hugh Y. H., "Series 64 Resistance Experiments on High-Speed Displacement Forms," Marine Technology, Vol. 2, No. 3, July, 1965.

APPENDIX A

SHIP DATA

Representative naval ship types are presented herein including the specific powers for Chapter 2 analysis. Also the fossil-fueled and nuclear cruiser characteristics are included. (Section 2.4.2)

TABLE A1 NAVY DISPLACEMENT SHIPS (R3)

Ship	Specific Power (hp/ton)	Length (ft) Water Line	Length (ft) Overall	Top Speed (knots)	Weight (Long Tons)	Power (hp)	Remarks
Destroyers							
DD 931	17.5		418	33	4,000	70,000	14 in Class
DDG 31	16.9		418	35	4,200	70,000	4 in Class
DDG 2	15.6		437	35	4,500	70,000	23 in Class
DDG 35	15.4		493	35	5,200	80,000	2 in Class
Escorts							
DLG 6	14.7		513	34	5,800	85,000	10 in Class
DLG 16	10.9		533	34	7,800	85,000	9 in Class
DLG 26	10.7		547	34	7,900	85,000	9 in Class
DD 963	10.0		560	33	8,000	80,000	Possible 30 in Class
DLGN 25	7.0	550	565	30	8,600	60,000	Nuclear
DLGN 35	6.5		564	30	9,200	60,000	Nuclear
DLGN 38	6.5		585	30	10,000	65,000	Nuclear
DLGN 36	6.4		596	30	10,200	65,000	Nuclear
Cruisers							
CG 10	6.9	664	673	33	17,500	120,000	3 in Class
CLG 3	6.9	600	610	32	14,600	100,000	6 in Class
CGN 9	4.6		721	30	17,400	80,000	Nuclear
Carriers							
CVA 41	3.3	900	979	33	64,000	212,000	3 in Class
CVA 59	3.0	990	1,039-47	35	78,000	280,000	4 in Class
CVA 63	2.9	990	1,047-72	35	80,800	280,000	3 in Class
CVAN 65	3.1	1,040	1,123	35	89,600	280,000	Nuclear
CVAN 68	2.9	1,040	1,092	35	91,400	280,000	Nuclear--Possible 3 in Class

TABLE A2 HIGH-SPEED SHIPS (R3)

Designation	Power	Gross Weight	Sea State	Top Speed	hp/Ton	Remarks
			Hydrofoils			
PCH-1	6,600	120	Calm	48	55	High Point Built
AGEH	28,000	320	Calm	87	87	Plainview Built
PGH-1	3,600	58	Calm	50	62	Flagstaff Built
PGH-2	3,200	58		50	55	Tucumcari Built
PHM	16,000	231		50	70	NATO Missile-Armed Patrol Boat
			Surface Effect Ships			
Low L/B	135,000	2,200	0 3	85 68	60	Designed
High L/B	23,000	1,000	0 3	46 38	23	Estimates
	48,000	2,000	0 3	52 45	24	
	105,000	4,000	0 3	58 51	26	
	250,000	10,000	0 3	62 58	25	
			Air-Cushion Vehicles			
7380 Voyageur	3,400	45.5	0	58	75	Built
7501 Viking	1,700	16	0	58	105	Built
SR-N3	3,900	41.5	0	81	93	Built
SR-N4	13,600	202	0	75	67	Built
BH.7 Wellington	3,400	57	0	75	60	Built
SES 100A	11,200	126	0	92	89	Built
SES 100B	13,500	105	0	92	128	Built
JEFFA	18,800	170	0	50	110	Designed
JEFFB	18,800	177	0	50	105	Designed

TABLE A2 (Continued) HIGH-SPEED SHIPS

Designation	Power	Gross Weight	Sea State	Top Speed	hp/Ton	Remarks
Multihull Ships						
SWATH	65,000	2,370		39	27	Estimates
	60,000	3,000		34	20	
	62,000	5,550		29	11	
Planing Craft						
PG-84	16,900	225	0	45	75	Built
CPIC	6,000	75	0	45	80	Built
SSP	6,400	190	0	25	34	Designed

TABLE A3 (M3)

CG 16 (Leahy)

)isplacement (tons)	5670 standard, 7800 full load
.ength (ft)	533
3eam (ft)	54.9
)raft (ft)	24.5
lissile launchers	2 twin Terrier surface to air (MK 10 Mod 5)
luns	4 - 3 in. 50 caliber (twin)
Anti-submarine	1 ASROC 8 - tube launcher 2 triple torpedo tubes (MK32)
lain engines	2 geared turbines; 85000 SHP, 2 shafts
3oilers	4 B & W
3peed (knots)	34
Complement	396 (31 officers, 365 enlisted) including squadron staff
:lectronics	NTDS SQS - 23 bow mounted sonar SPS- 10 and SPS - 48 SPS - 37

TABLE A4 (M3)

CGN 25 (Bainbridge)

isplacement (tons)	7600 standard, 8580 full load
ength (ft)	550 waterline, 565 overall
eam (ft)	57.9
raft (ft)	29
issile launchers	2 twin Terrier
uns	4 - 3 in. (76 mm) 50 caliber (twin)
/S weapons	1 ASROC 8 tube launcher 2 triple torpedo tubes MK 32
ain engines	2 geared turbines approximately 60,000 SHP; 2 shafts
eactors	2 pressurized water reactors D-2G (GE)
peed (knots)	30 +
omplement	approx 450 (26 officers, 425 enlisted)
lectronics	SQS - 23 bow mounted sonar SPS - 52 3-D, SPS-10 SPS - 37 search radar

TABLE A5 (M3)

CG - 26 (Belknap class)

Displacement (tons)	6570 standard, 7930 full load
Length (ft)	547
Beam (ft)	54.8
Draft (ft)	28.8
issile launchers	1 twin Terrier/ASROC launcher (MK 10 Mod 7)
Anti-submarine weapons	ASROC 2 triple torpedo tubes (MK 32)
uns	1 5 in. 54 caliber dual purpose 2 3 in. (76 mm) 50 caliber anti-aircraft (single)
elicopters	1 SH-2D LAMPS
ain Engines	2 geared turbines (GE) 85,000 SHP, 2 shafts
oilers	4 Babcock and Wilcox
peed (knots)	34
omplement	418 (31 officers, 387 enlisted) including squad staff
lectronics	SQS - 26 bow mounted sonar NTDS SPS48 - 3D, SP-10 SP37 or SPS-40

TABLE A6 (M3)

CGN - 35 (Truxton class)

splacement (tons)	8200 standard, 9200 full load
ngth (ft)	564
am (ft)	58
aft (ft)	31
ssile launches	1 twin Terrier/ASROC launcher MK10 Mod 7 Chaffroc
ns	1 5 in. (127 mm) 54 caliber dual purpose 2 3 in. (76 mm) 50 caliber A/A
ti-submarine weapons	4 MK 32 fixed torpedo tubes Helicopters
in engines	2 gear turbines 60,000 SHP; 2 shafts
actors	2 PWR D2G (GE)
eed (knots)	30+
mplement	approximately 500 (35 officers, 465 enlisted)
ectronics	bow mounted SQS - 26, NTDS, SPS - 48 3-D and SPS-10 search radars, SPS-40 search radar, TACAN

APPENDIX B

DETAILS OF NAVAL ARCHITECTURE ANALYSIS

This Appendix contains details of the computer parametric weight dels used in Chapter 3. After specifically detailing how the specific el consumption was modeled in Section B-1, Section B-2, B-3, B-4, and 5 elaborate on the specific ship type weight models and explain why sulting trends noted in Chapter 3 occured.

B1 SPECIFIC FUEL CONSUMPTION MODEL

To determine the burnable fuel (95% of the total fuel weight which an be pumped from the fuel tanks by the fuel transfer system) two formulas ere utilized.

Conventional Displacement Ship

$$W_f = \frac{(P_E)(SFC)(R)}{(V_E)(2020)} \tag{B-1.1}$$

High Performance Ships (Brequet Formula)

$$W_f = 1.108 \frac{\Delta \left\{ \exp\left[\frac{(R)(SFC)(P_E)}{(2240)(\Delta)(V_E)}\right] - 1 \right\}}{\exp\left[\frac{(R)(SFC)(P_E)}{(2240)(\Delta)(V_E)}\right]} \tag{B-1.2}$$

where W_f = weight of fuel (tons)

P_E = endurance power (shaft horsepower)

R = range (nm)

V_E = endurance speed (kts)

Δ = full load displacement (tons)

SFC = specific fuel consumption (lbm/SHP hr)

= f(propulsion plant type, P_E/P_S)

where P_S = installed power

To analyze the fossil-fueled ships, a survey of propulsion plants rom (L2) was used for the computer models where Table B-1.1 summarizes the esults.

Figures B-1.1, B-1.2, B-1.3, and B-1.4 summarize SFC versus P_E/P_S where:

δ_o = 5.0, 10.0 are gas turbine plants

δ_o = 20.0, 30.0 are steam plants

δ_o = 50.0 are medium speed diesel plants

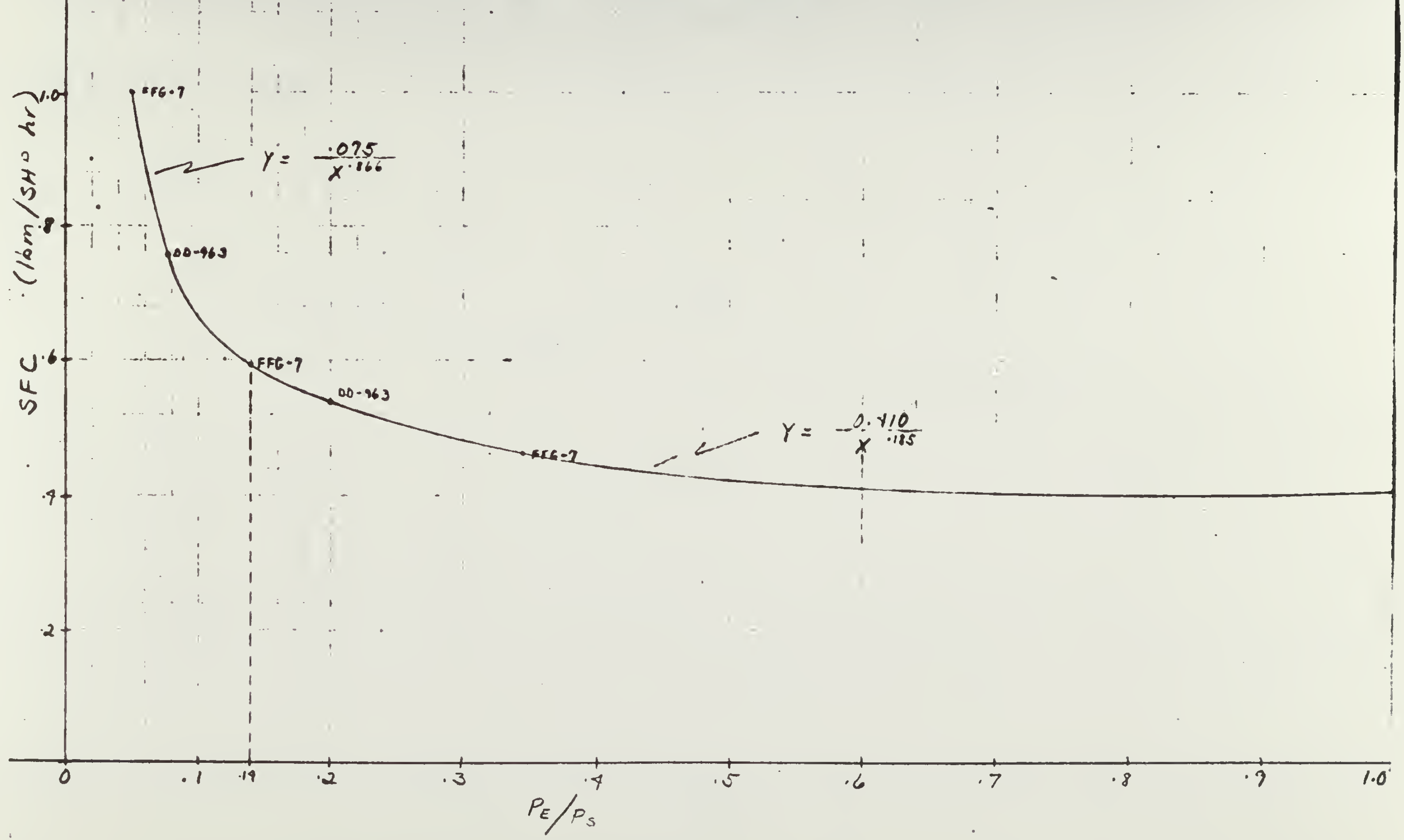
δ_o = 100.0, 120.0 are low speed diesel plants

TABLE B1-1

PROPULSION PLANT δ_a AND SFC PARAMETERS

PLANT TYPE	δ_a (lbm/SHP)	MIN SFC (lbm/SHP hr)
Aircraft Derivative Gas Turbine (3rd gen.)	5.0	0.38
Heavy Marine Gas Turbine/ COGAS (2nd gen.)	10.0	0.40
Pressure Fired Boiler	20.0	0.42
1200# Steam	30.0	0.42
Medium Speed Diesel 150 - 750 RPM	50.0	0.34
Low Speed Diesel 150 RPM	100.0, 120.0	0.32

FIGURE B1-1 SFC vs. P_E/P_S for Gas Turbine Propulsion Plants ; δ_o = 5.0, 10.0



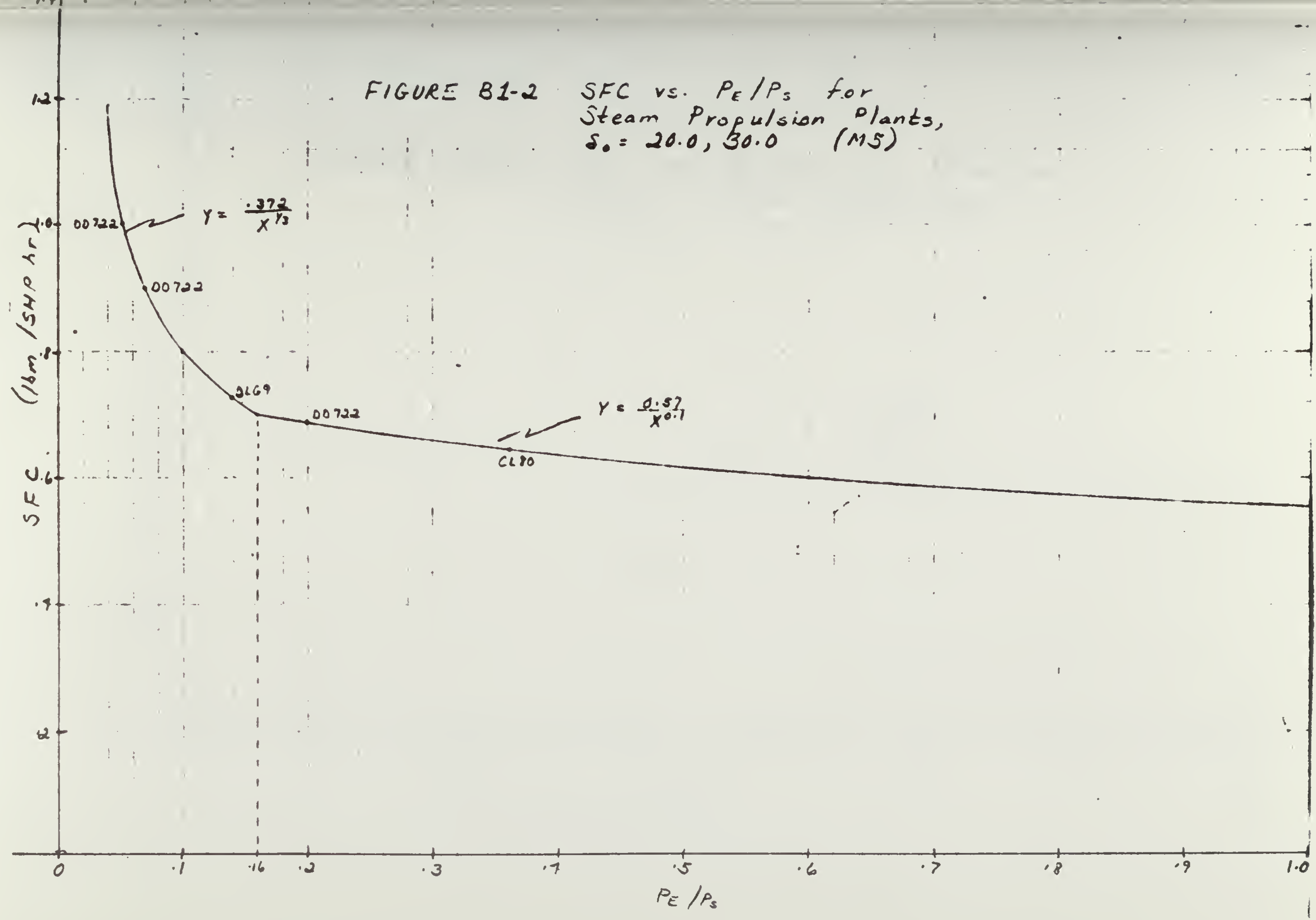


FIGURE B1-2 SFC vs. P_E/P_s for Steam Propulsion Plants, S_o = 20.0, 30.0 (MS)

FIGURE B1-3 SFC vs P_E/P_S for Medium Speed Diesel Propulsion Plants, $\delta_0 = 50.0$

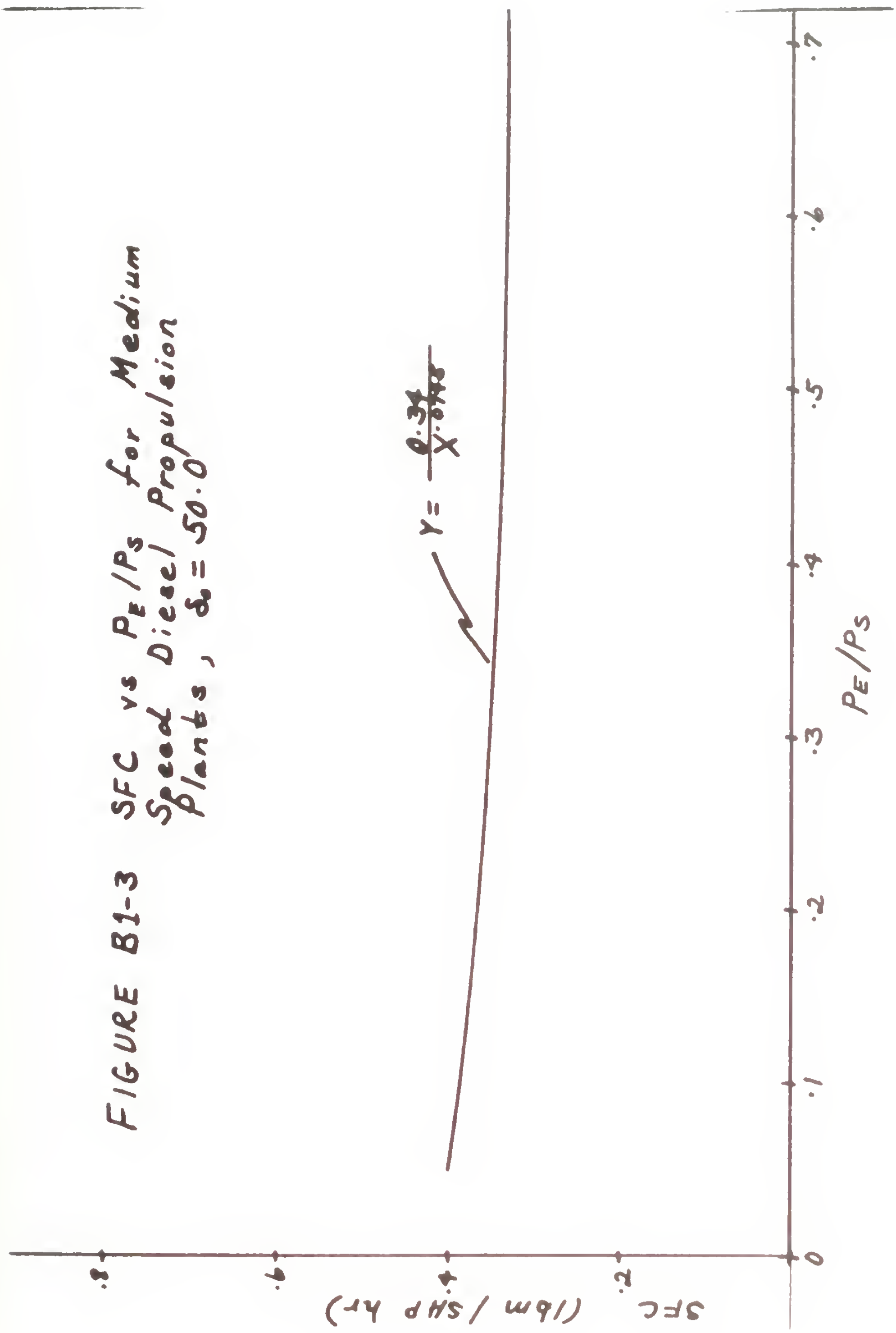
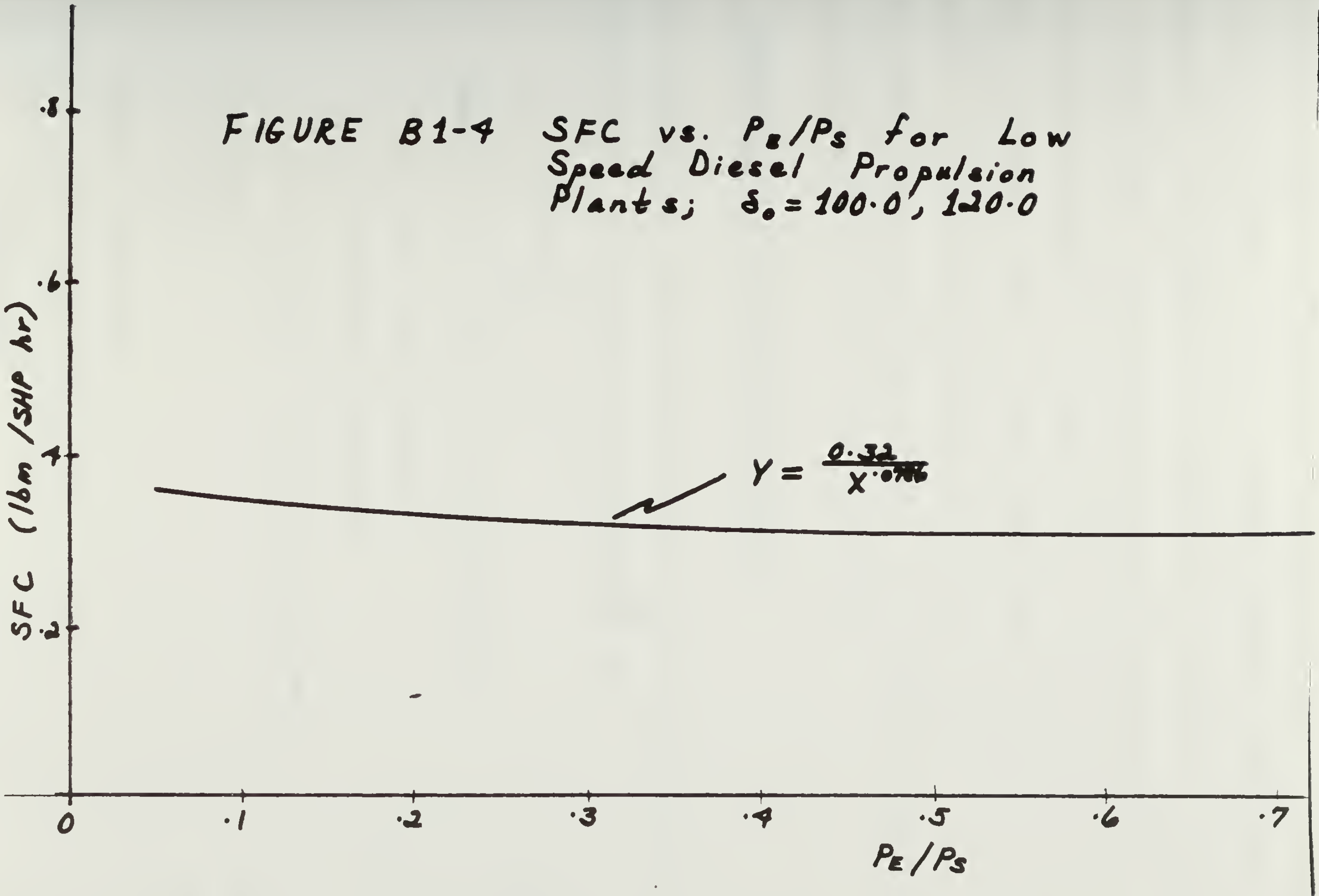


FIGURE B1-4 SFC vs. P_E/P_S for Low Speed Diesel Propulsion Plants; $\delta_o = 100.0', 120.0$



e figures were generated by studying for the gas turbine and steam plants, epresentative ships and their SFC for varying P_g/P_s ratios. For instance, the case of the DD-963, the four installed LM2500's (80,000 SHP) operate minimum SFC = 0.41 lbm/SHP hr at $P_g/P_s = 1.0$, i.e. when the endurance eed = maximum speed. If the speed of the ship were decreased to a 6,400 P requirement, presumably, the ship would be relying on two gas turbines erating at 3200 SHP each. The SFC = 0.76 lbm/SHP hr for $P_g/P_s = 0.8$ at is point. A similar plot was made for the steam plant.

The diesel plants were based, however, on horsepower versus RPM for pical propeller load curves as contained in (H3).

2.1 Conventional Displacement Ship Details

The conventional displacement ship weight model was based on the ndel study (M5). To determine the ship dimensions

$$L = \left[\frac{(\Delta)(34.997)}{C_v}\right]^{1/3} \qquad \text{(B2.1)}$$

where L = ship length between perpendiculars

Δ = full load displacement

C_v = volumetric coefficient

$\nabla = \Delta(34.997)$ = volumetric displacement

$$B = L/(L/B) \qquad \text{(B2.2)}$$

$$D = B/(B/H) \qquad \text{(B2.3)}$$

where B = ship beam

L/B = length-to-beam ratio

D = ship draft

B/H = beam-to-draft ratio

To understand the overall specific propulsion weight limits that resulted in Chapter 3, one must examine the conventional displacement ship weight fraction breakdown in Figure B2-1. It can be seen that for a 12% weight fraction, since the weight left can be used for fuel and the propulsion plant, increasing displacement will allow for a higher weight fraction for the fuel and propulsion plant.

Examining the power required for certain maximum sustained speeds as a function of Δ in Figure B-2.2 reveals that speeds above 30 knots require very high shaft horsepower. Since propulsion weight = δ_ox SHP, high speeds and high specific propulsion weights take greater and greater weight fractions.

Furthermore, for the fossil-fueled conventional displacement ship, the fuel weight fraction also impacts upon the weight left for the propulsion plant as shown in Figures B2-3 through B2-6. Since the fuel weight fraction decreases with increasing ship displacement for a certain cruise speed, the higher displacement ships can therefore accomodate longer ranges for a certain plant type. It should be noted that although the low speed diesel plant in Figure B2-6 has the lowest fuel weight fractions, due to its low SFC, the fact that this plant's $\delta_o \approx 100.0 - 120.0$ lbm/SHP, greatly negates the savings in fuel.

B2.2 High Performance Displacement Ship Details

The high performance displacement ship was a hypothetical design based on the Series 64 Model 4803 monohull displacement hull (Y1). The ship was designed to the HOC hydrofoil design criteria, which as seen in Table B2-1, imposed much more stringent weight and volume allowances, as opposed to the latest conventional gas turbine ship, the FFG-7.

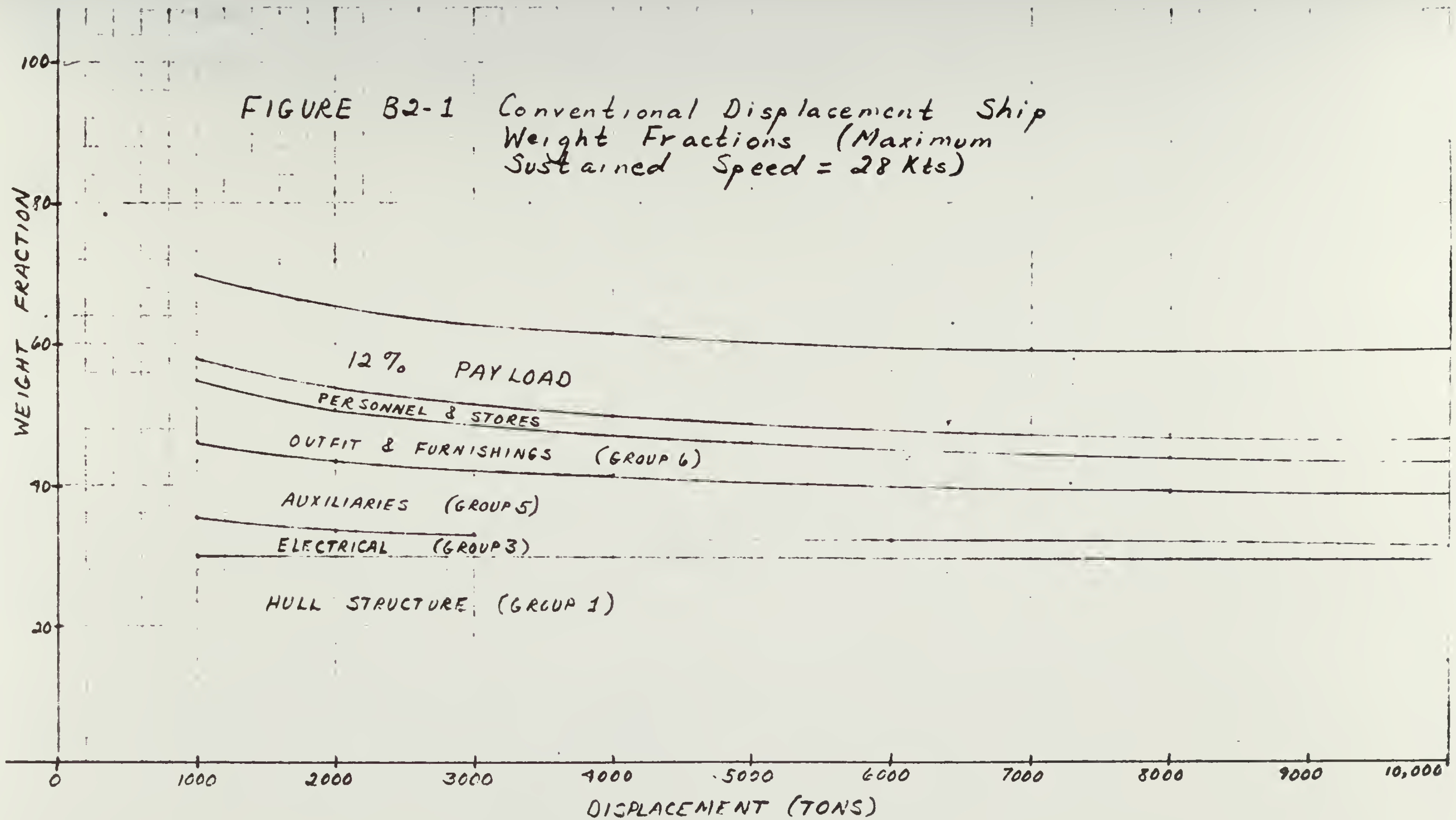


FIGURE B2-1 Conventional Displacement Ship Weight Fractions (Maximum Sustained Speed = 28 Kts)

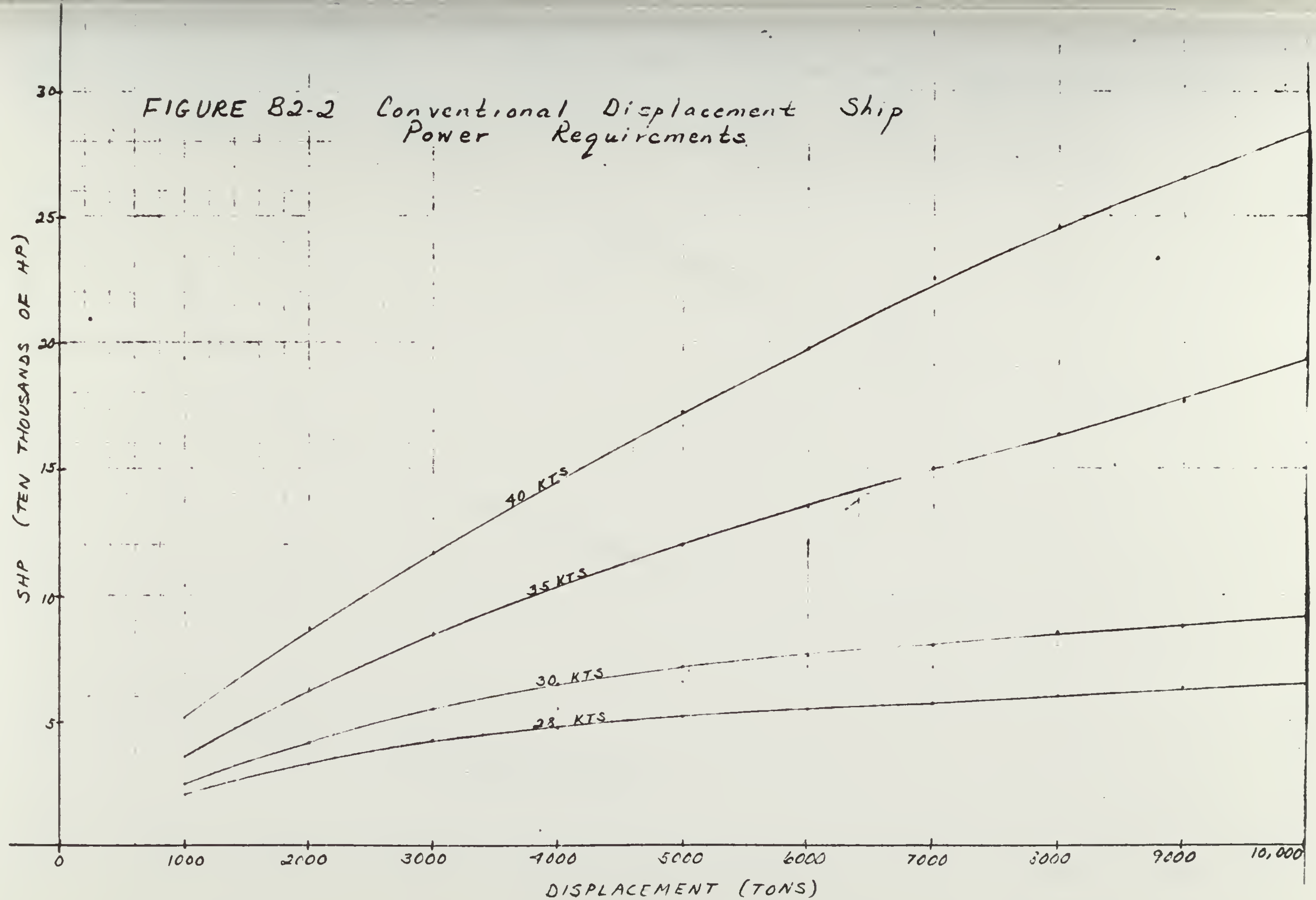


FIGURE B2-2 Conventional Displacement Ship Power Requirements

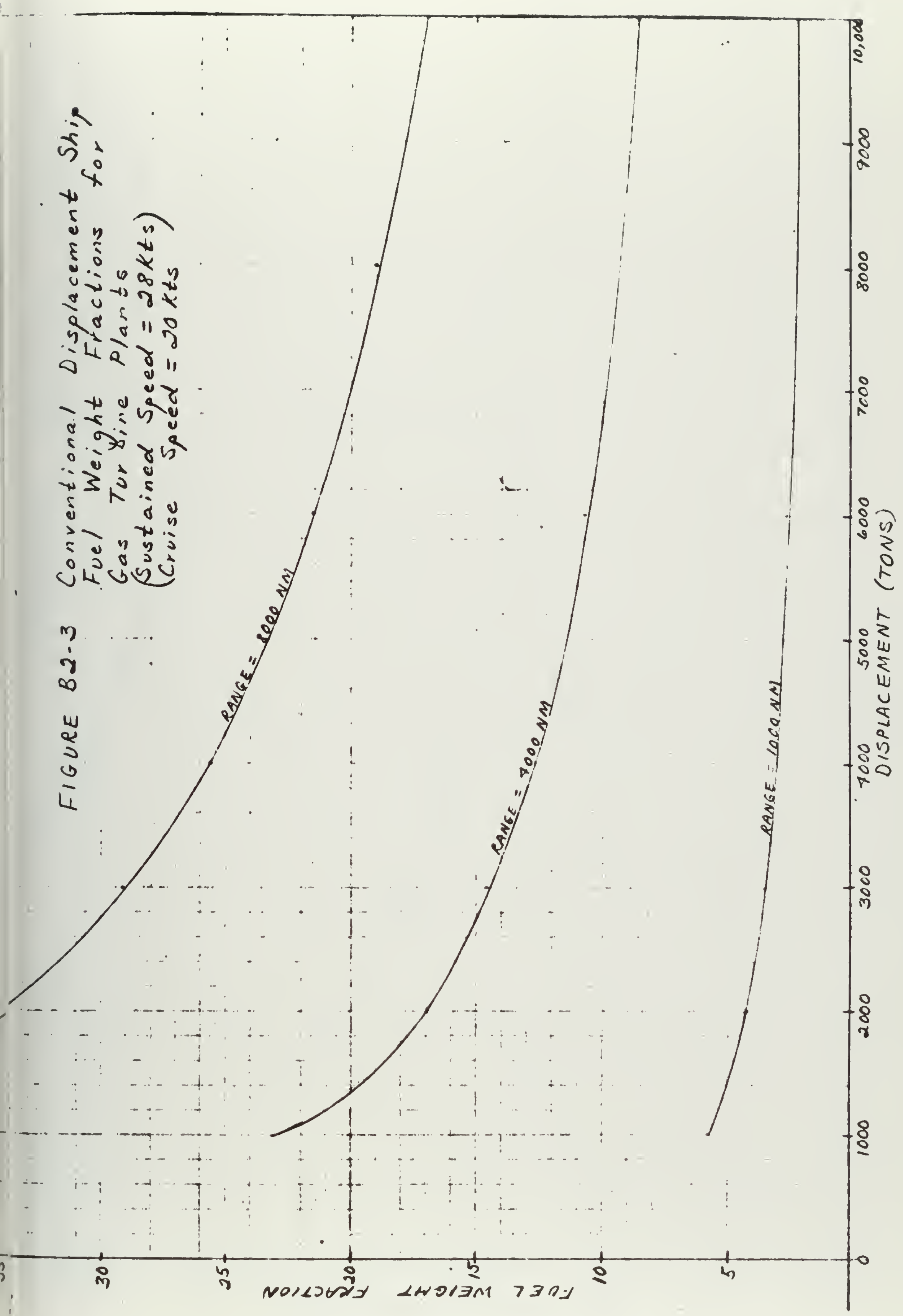


FIGURE B2-3 Conventional Displacement Ship Fuel Weight Fractions for Gas Turbine Plants
(Sustained Speed = 28Kts)
(Cruise Speed = 20 Kts)

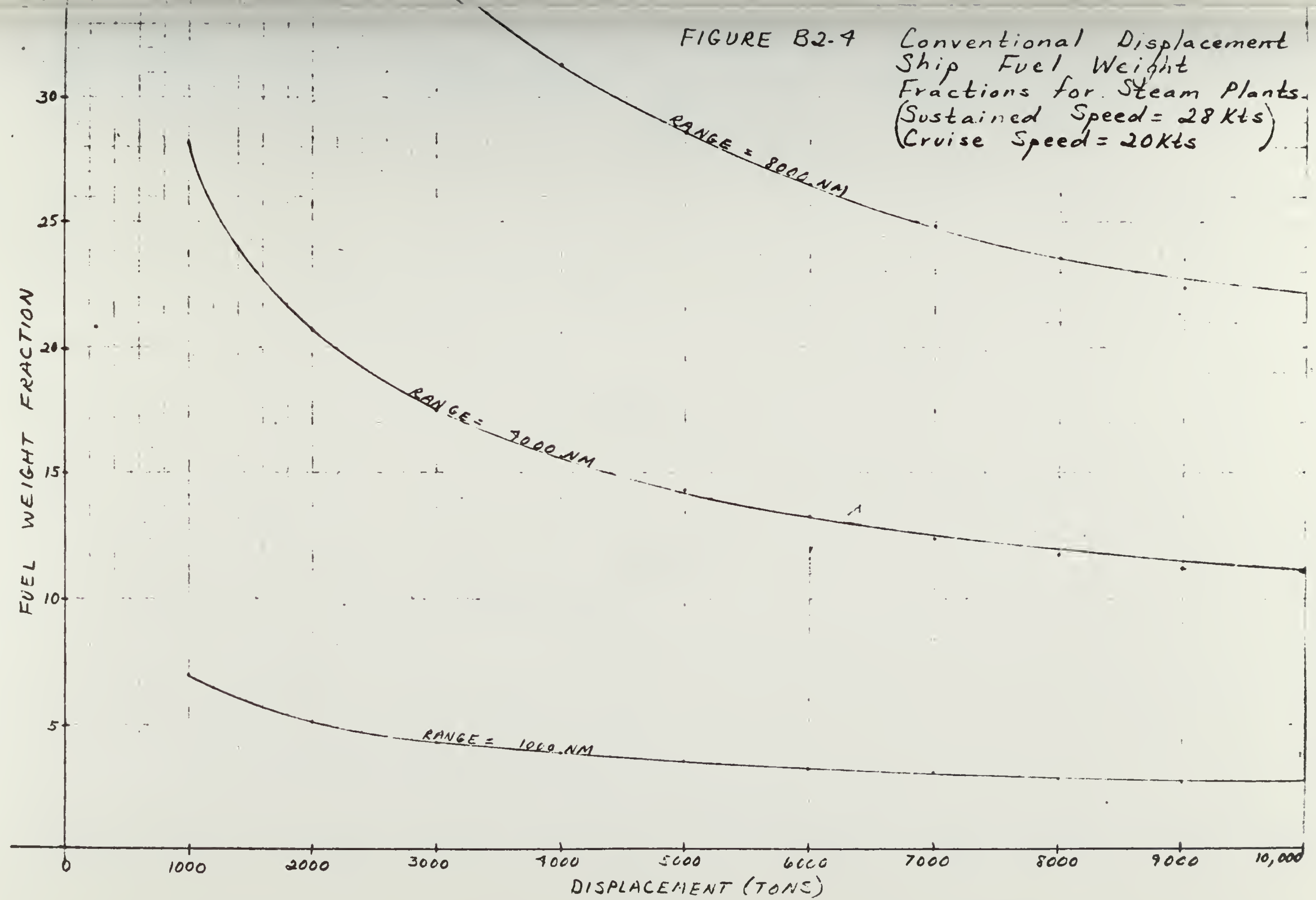


FIGURE B2-4 Conventional Displacement Ship Fuel Weight Fractions for Steam Plants (Sustained Speed = 28 Kts) (Cruise Speed = 20 Kts)

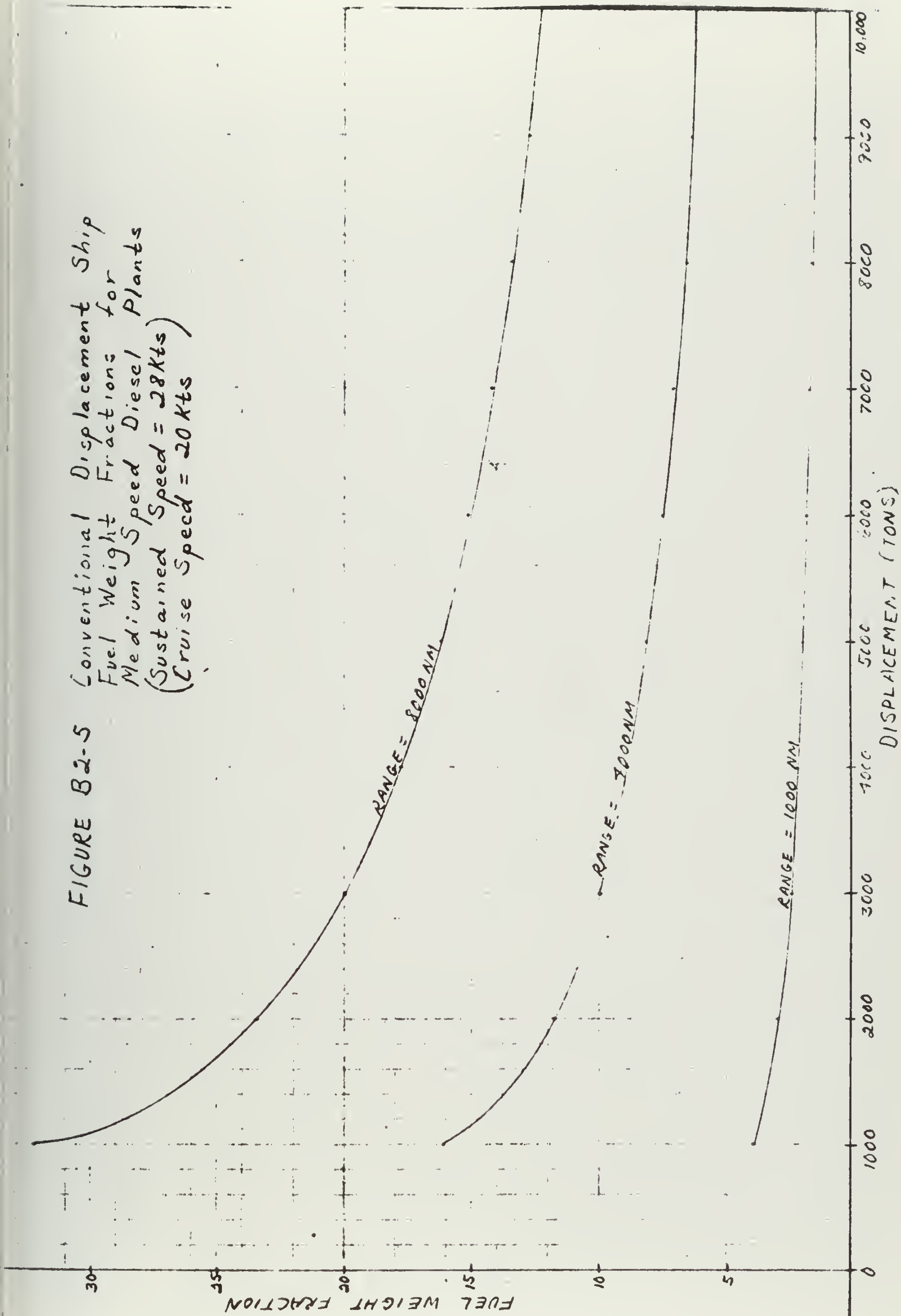
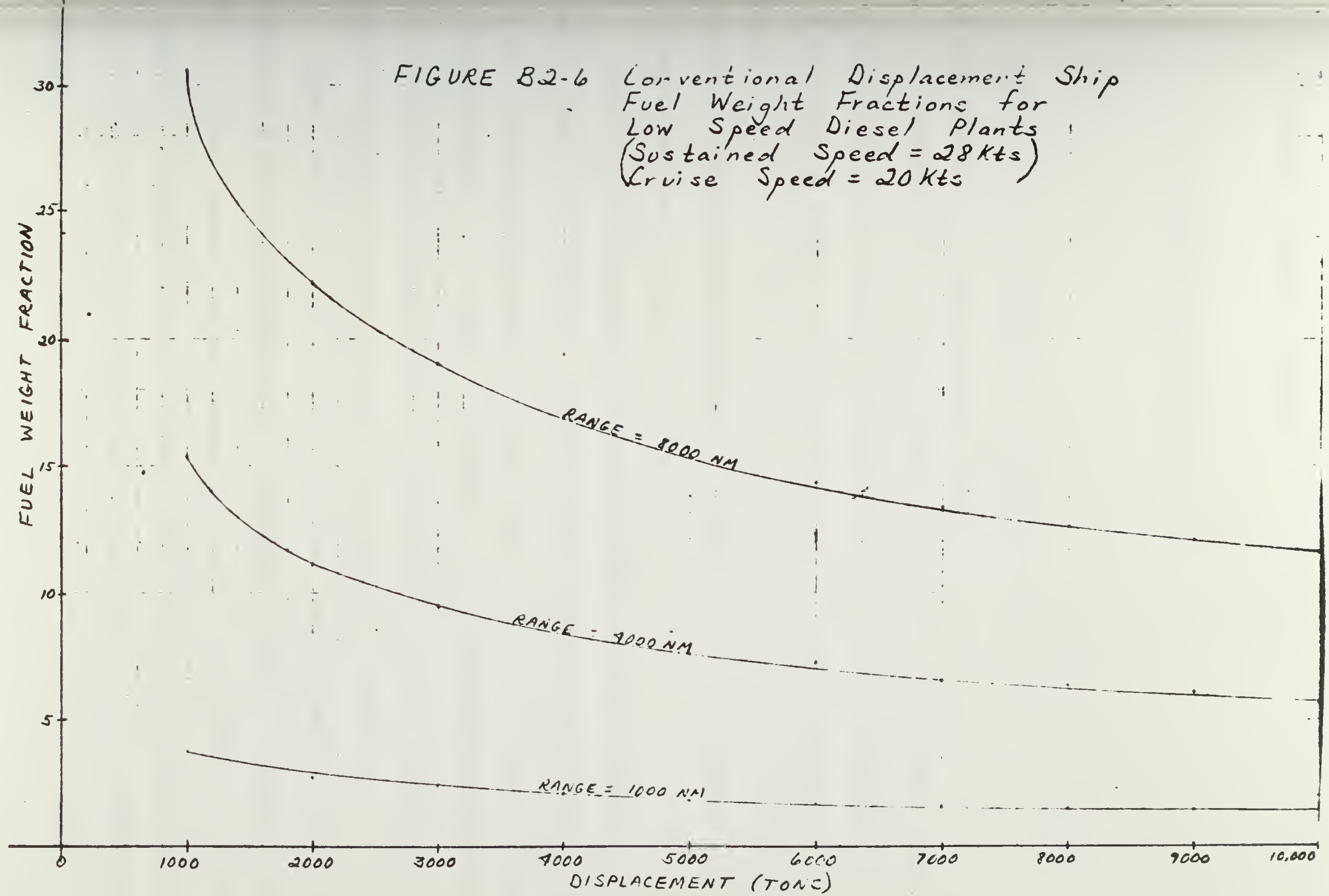


FIGURE B2-5 Conventional Displacement Ship Fuel Weight Fractions for Medium Speed Diesel Plants (Sustained Speed = 28Kts) (Cruise Speed = 20Kts)

FIGURE B2-6 Conventional Displacement Ship Fuel Weight Fractions for Low Speed Diesel Plants (Sustained Speed = 28 Kts Cruise Speed = 20 Kts)



To determine the ship dimensions:

$$L = \left[\frac{(\Delta)(34.997)(B/H)(L/B)^2}{C_B} \right]^{1/3}$$

(B2.4)

where C_B = block coefficient = $\frac{\nabla}{(L)(B)(T)}$

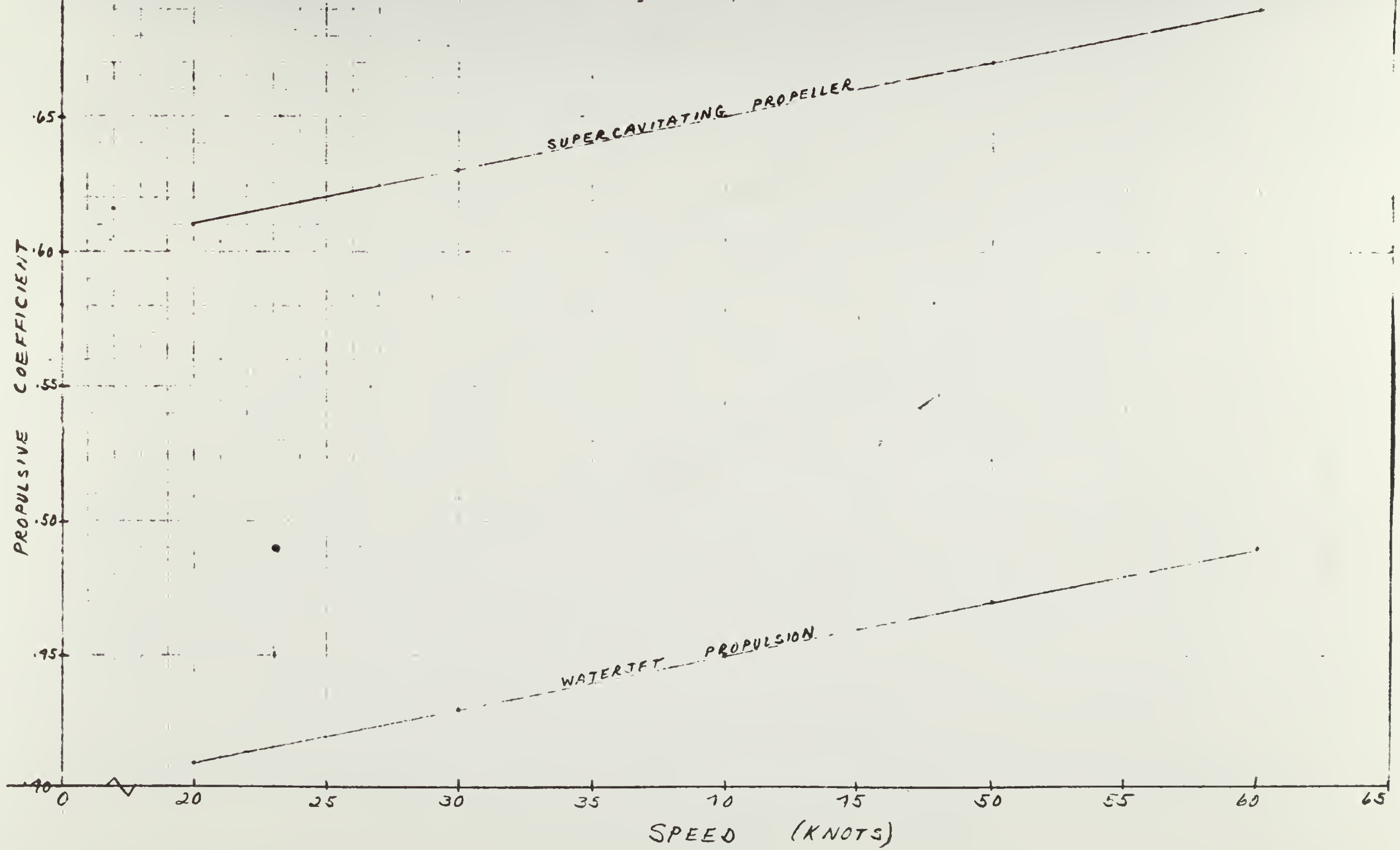
The beam and draft were determined as before.

To determine the power requirements, a Series 64 calculation based on the ITTC line and a residuary resistance input of Table 2, reference (Y1) for this model was made. After a 10% allowance for appendage drag and a correction factor of 23.75% including 10% margin, propulsive coefficients based on a consensus of sources shown in Figure B2-7 were utilized to get the power requirements shown in Figure B2-8.

Since this ship was based on applying hydrofoil design criteria to surface displacement monohulls, constant weight fractions corresponding to the HOC were utilized as shown in Figure B2-9. This is of course unrealistic, but the purpose was to analyze the effects of high performance design criteria on a Series 64 displacement hull, not synthesize a design. HOC design criteria and the FFG7 design criteria are compared in Table B2-1.

Again, analyzing the weight fractions for the HPDS reveals why certain propulsion plant weight limits exist. Although the HPDS is a more efficient hull at higher speeds than the conventional hull, the high shaft horsepowers required at the higher speeds dictates low δ_e in the range of gas turbines. This can be readily seen by adding Figures B2-10 and B2-11 for various full speeds and ranges. Furthermore, since the waterjet propulsive coefficient

FIGURE B2-7 Propulsive Coefficient vs Speed for High Performance Displacement Ship



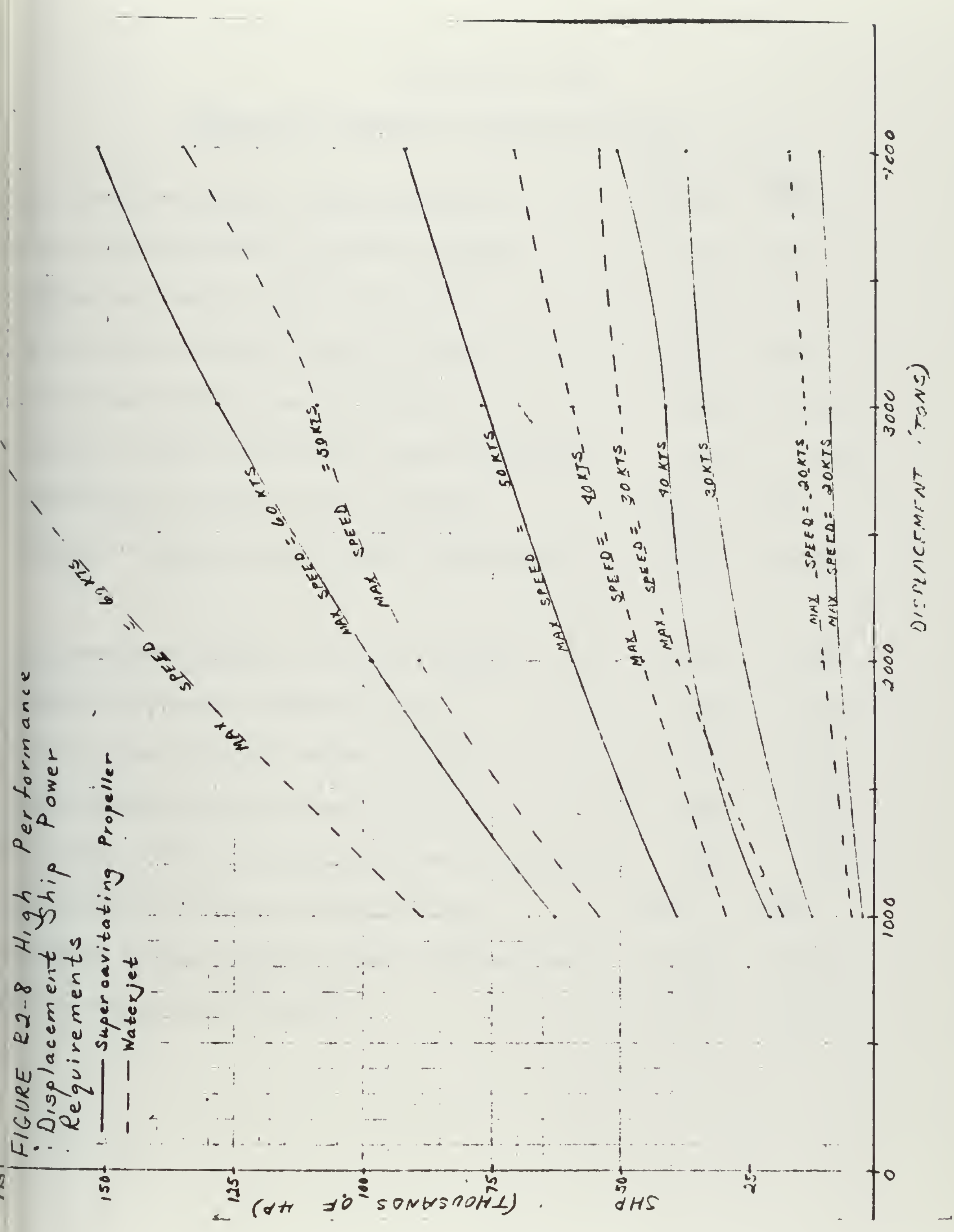


FIGURE B2-8 High Performance Displacement Ship Power Requirements

TABLE B2-1 (F5)

PERFORMANCE PARAMETERS FOR HOC AND FFG-7

	HOC	FFG-7
ull structure specific weight (lbm/ft^3)	2.55	5.73
ain propulsion specific weight (lbm/SHP)	3.24	14.4
uxiliaries specific weight (lbm/ft^3)	.167	1.07
lectric plant specific weight (lbm/KW)	51.82	97.12
hip systems specific weight (lbm/ft^3)	.465	1.29
ther ship operations specific weight (lbm/ft^3)	.114	.349
abitability specific weight (lbm/man)	594.7	1391.4
ersonnel stowage specific weight (lbm/man-day)	27.81	26.52
ain propulsion specific volume (ft^3/SHP)	1.00	1.60
uxiliaries specific volume (ft^3/ft^3)	.29	.123
lectric plant specific volume (ft^3/KW)	5.07	6.04
hip systems specific volume (ft^3/ft^3)	.057	.120
ther ship operations specific volume (ft^3/ft^3)	.096	.118
abitability specific volume (ft^3/man)	529.8	544.7
ersonnel stowage specific volume (ft^3/man-day)	1.67	1.75
uel system density (lbm/ft^3)	44.25	43.84

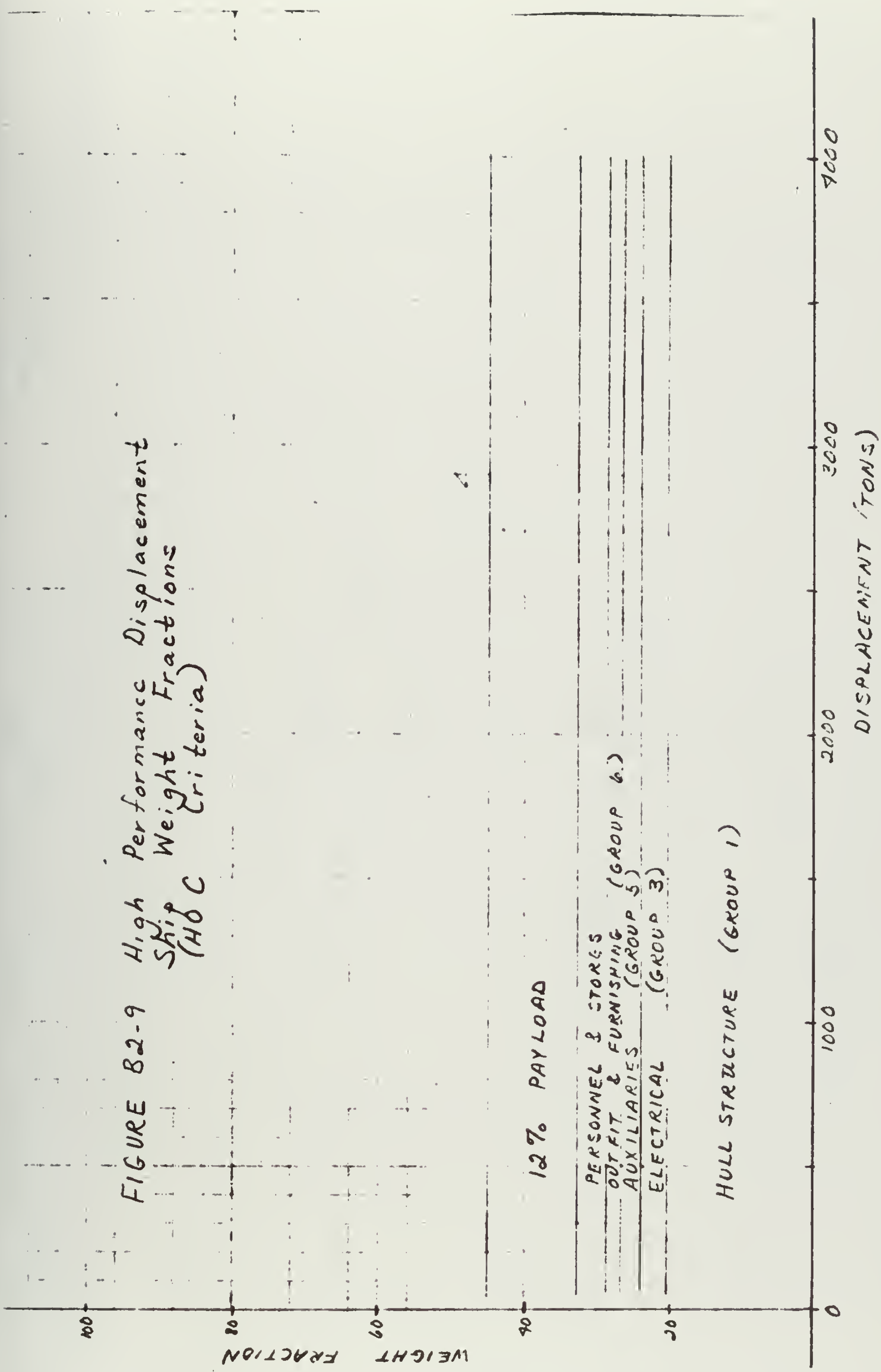


FIGURE B2-9 High Performance Displacement Ship Weight Fractions (HOC Criteria)

FIGURE B2-10 High Performance Displacement Ship Propulsion Weight Fraction

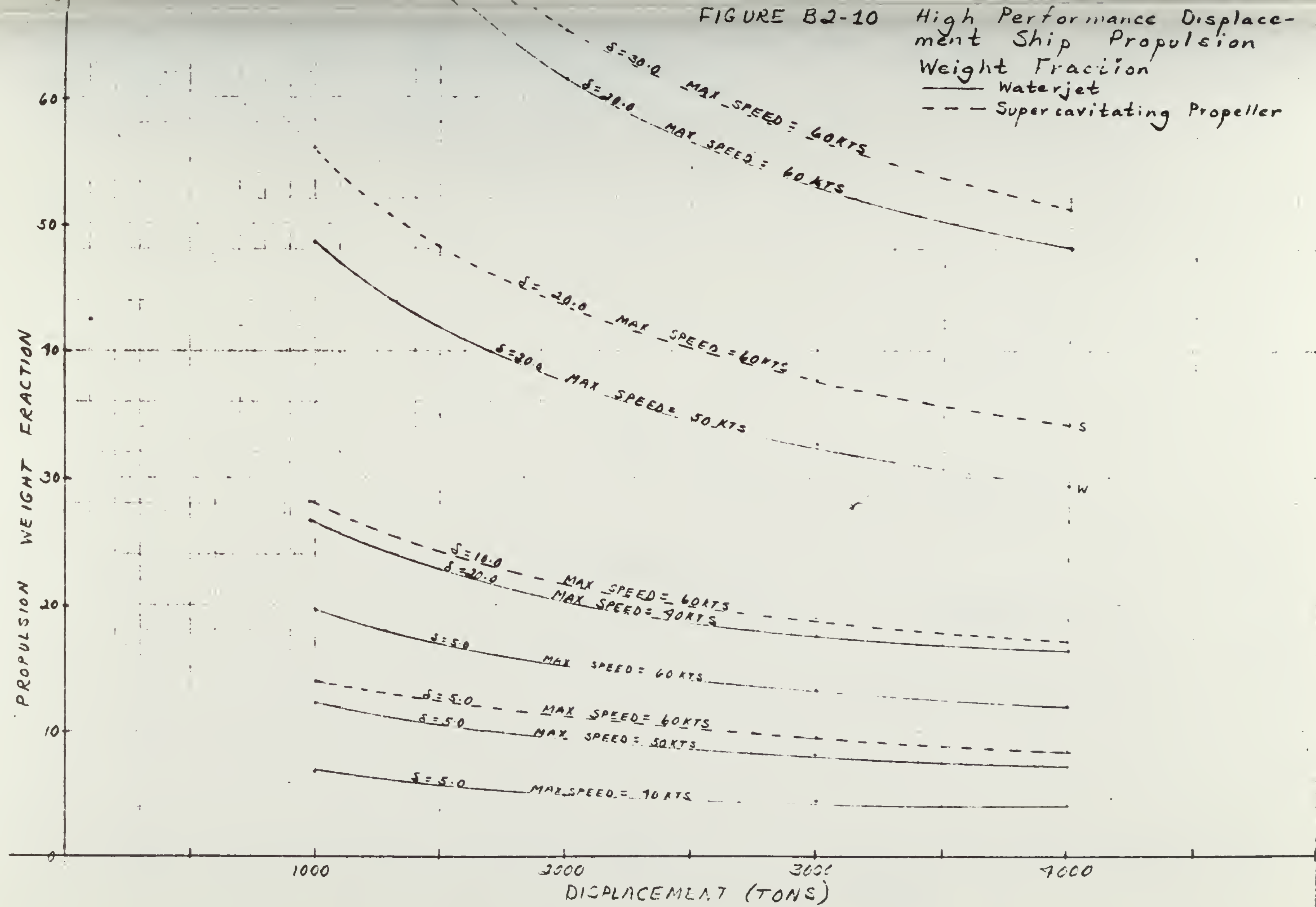
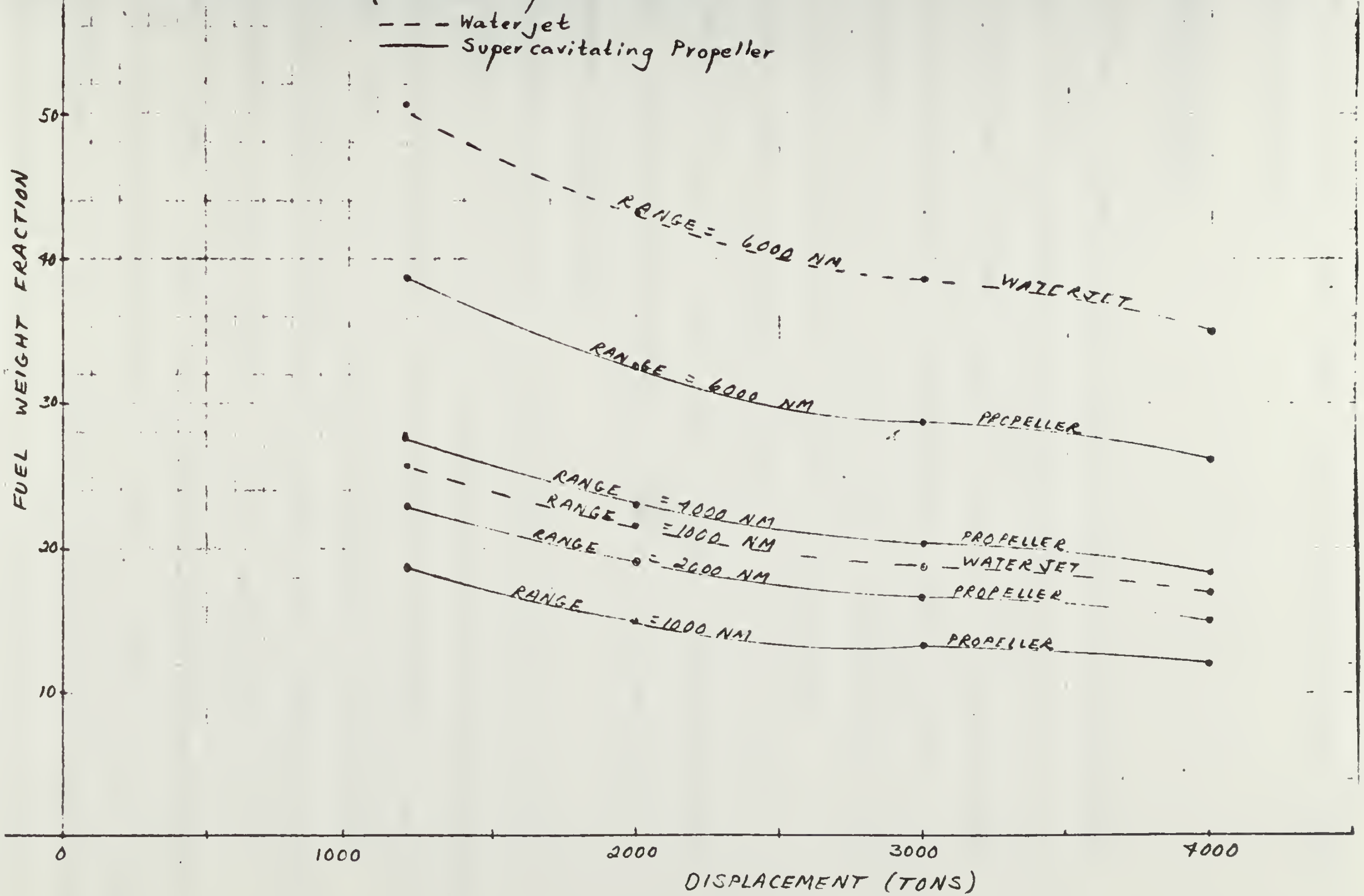


FIGURE B2-11 High Performance Displacement Ship Fuel Weight Fractions for Gas Turbine Propulsion
(Maximum Speed = 60 Kts)
(Cruise Speed = 20 Kts)



is much lower than for the supercavitating propeller, the waterjet propulsion system requires more weight since the shaft horsepower requirements are so much greater.

B2.3 Hydrofoil Details

The hydrofoil parametric weight model was based on the PHM and the HOC design. The 230 ton PHM drag curves and weight fractions were used to represent the minimum displacement hydrofoil and the 1278 ton HOC drag curves and weight fractions for the maximum displacement hydrofoil. Since no 750 ton hydrofoil existed, the drag and weight fractions curves shown in Figures B2-12 and Table B2-2 were fitted to fill this gap.

Figure B2-13 shows the hydrofoil weight fractions that resulted. It should be noted that the foil system grows to about a 25% weight fraction at 2000 tons, a growth that forces design reductions in other areas in order to produce a feasible ship.

As in the case of the HPDS, the fossil-fueled hydrofoil is limited to gas turbine plants, as can be seen by analyzing the hydrofoil power requirements and fuel weight fractions. For the hydrofoil displacements examined, takeoff speed is 25 - 30 knots. Therefore, utilizing for the propeller version a separate hullborne subcavitating propeller and a foilborne supercavitating propeller and also examining a waterjet system, SHP versus Δ was predicted as shown in Figures B2-14 and B2-15 (propulsive coefficients were based on a consensus of sources and are shown in Figure B2-16.) Although the shaft horsepower is not high, the waterjet propulsion does greatly increase weight fraction requirements as opposed to the supercavitating propeller as shown in Figures B2-17 and B2-18 to the point that δ_s<10.0 lbm/SHP are required.

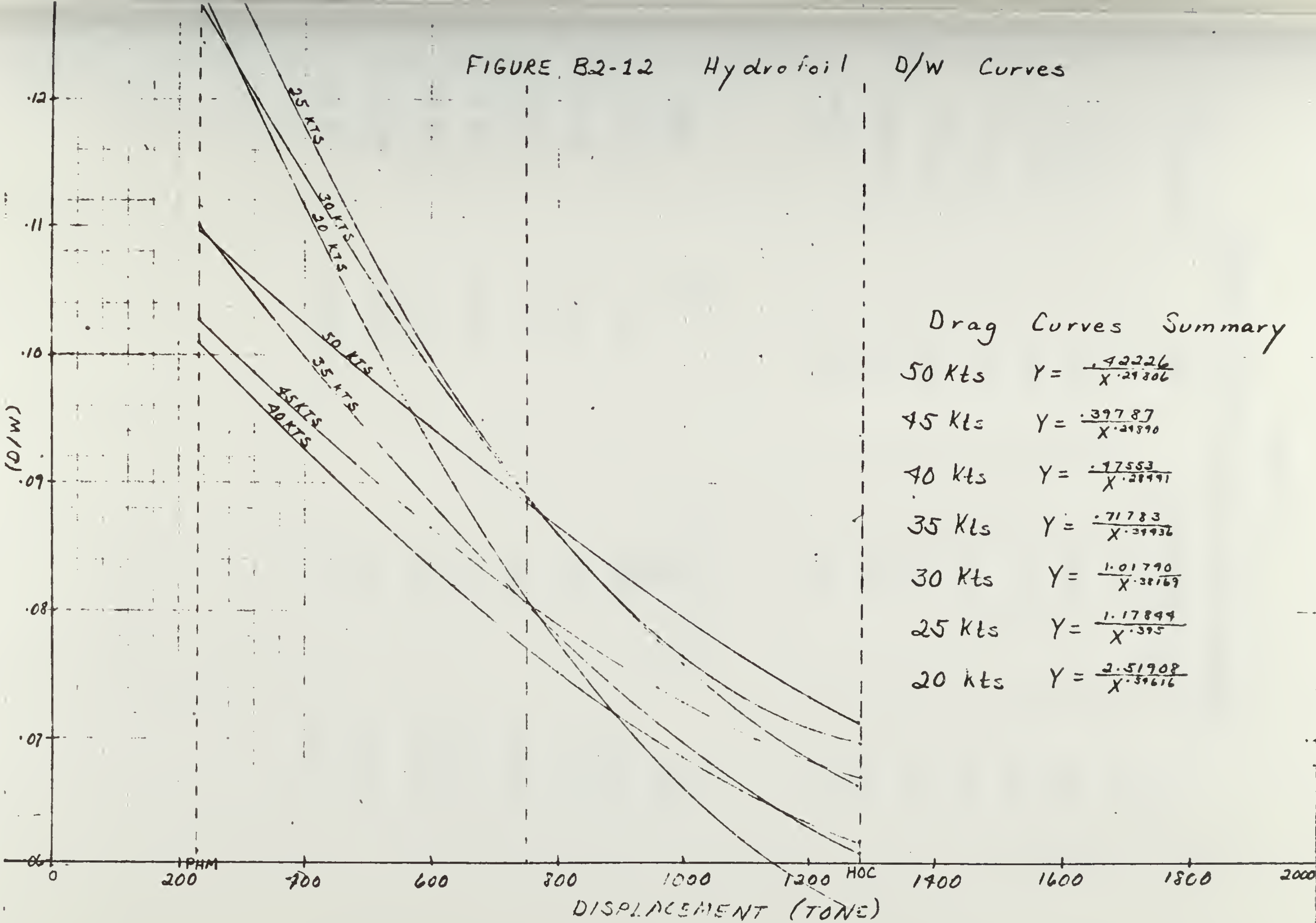


FIGURE B2-12 Hydrofoil D/W Curves

TABLE B2-2

HYDROFOIL WEIGHT AND DRAG CHARACTERISTICS

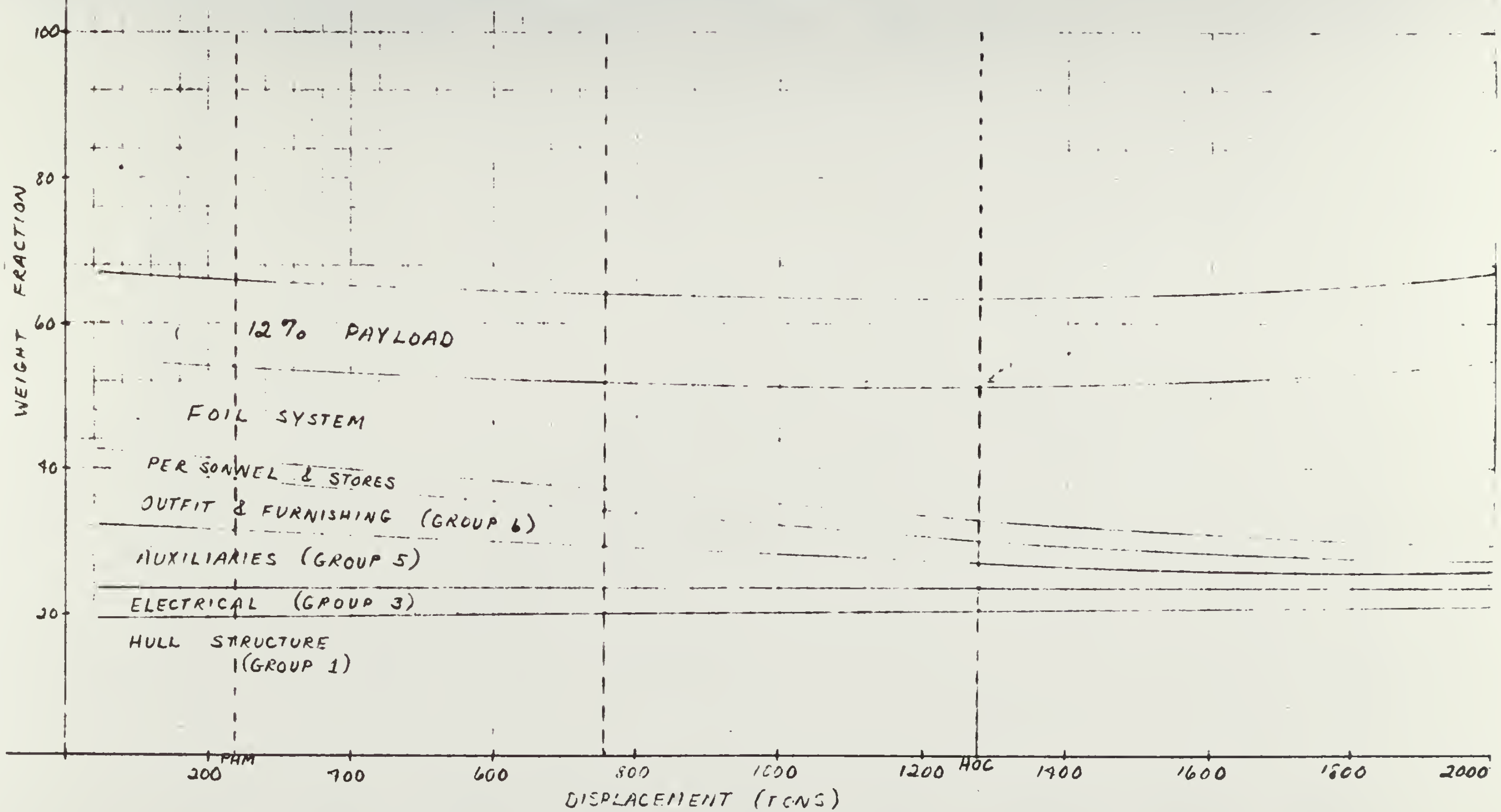
WT. FRACTION	PHM	750 TON EXTRAP	HOC
Δ	230	750	1278
$\frac{\text{Group 1}}{\Delta}$	.199	.200	.202
$\frac{\text{Group 3}}{\Delta}$	.040	.038	.036
$\frac{\text{Group 5}}{\Delta}$	.077	.052	.027
$\frac{\text{Group 6}}{\Delta}$	.069	.054	.040
Personnel	.028	.025	.023
Foil	.132	.150	.184

SPEED	PHM D/W	750 TON EXTRAP D/W	HOC D/W
20 KTS	.12923	.06776	.05065
25 KTS	.13754	.08623	.06986
30 KTS	.12772	.08134	.06637
35 KTS	.11034	.07344	.06113
40 KTS	.10127	.07236	.06218
45 KTS	.10278	.07658	.06707
50 KTS	.10958	.08173	.07161

[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

FIGURE B2-13 Hydrofoil Weight Fraction
(Maximum Speed ≈ 50Kts)



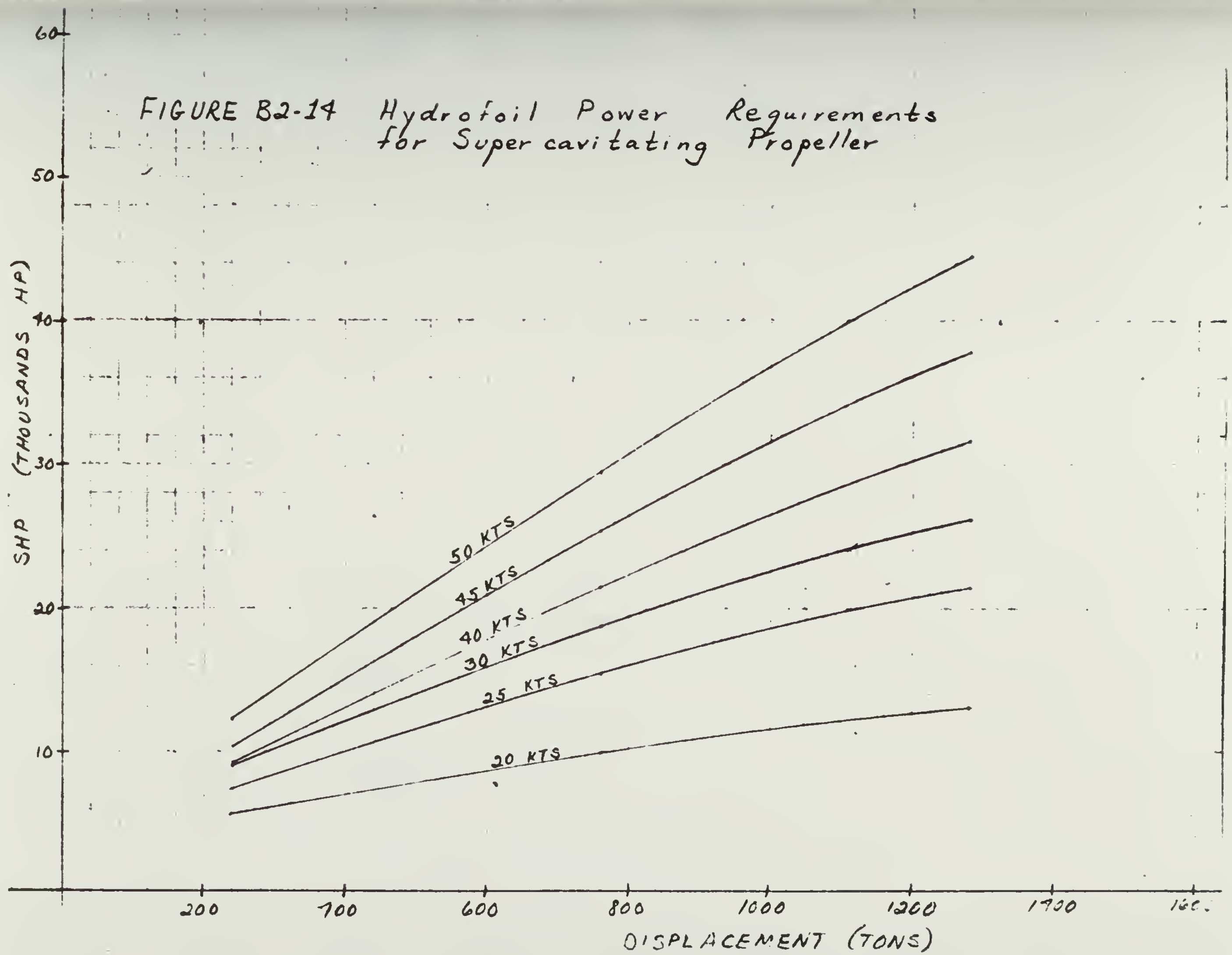


FIGURE B2-14 Hydrofoil Power Requirements for Supercavitating Propeller

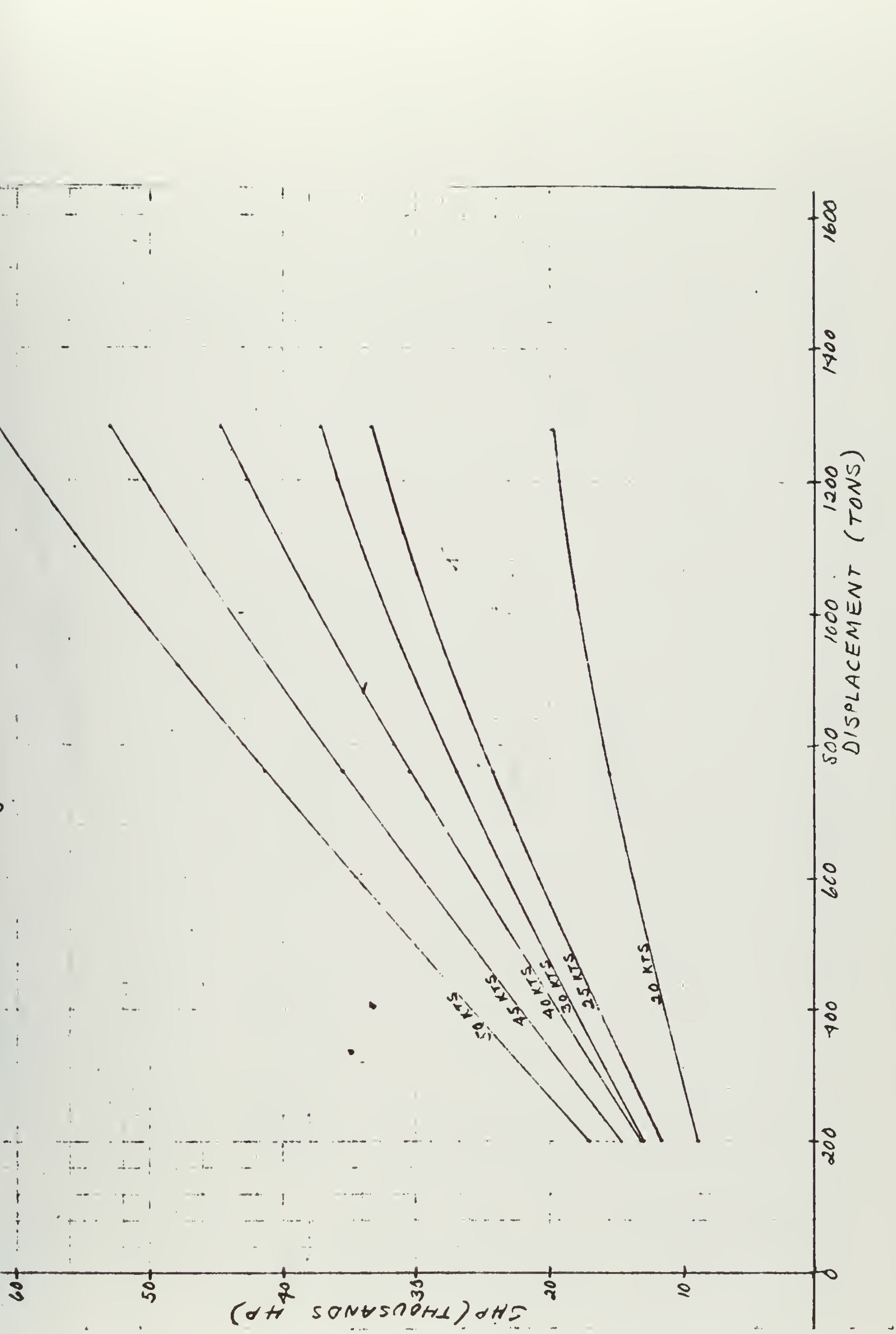


FIGURE B2-15 Hydrofoil Power Requirements for Waterjets

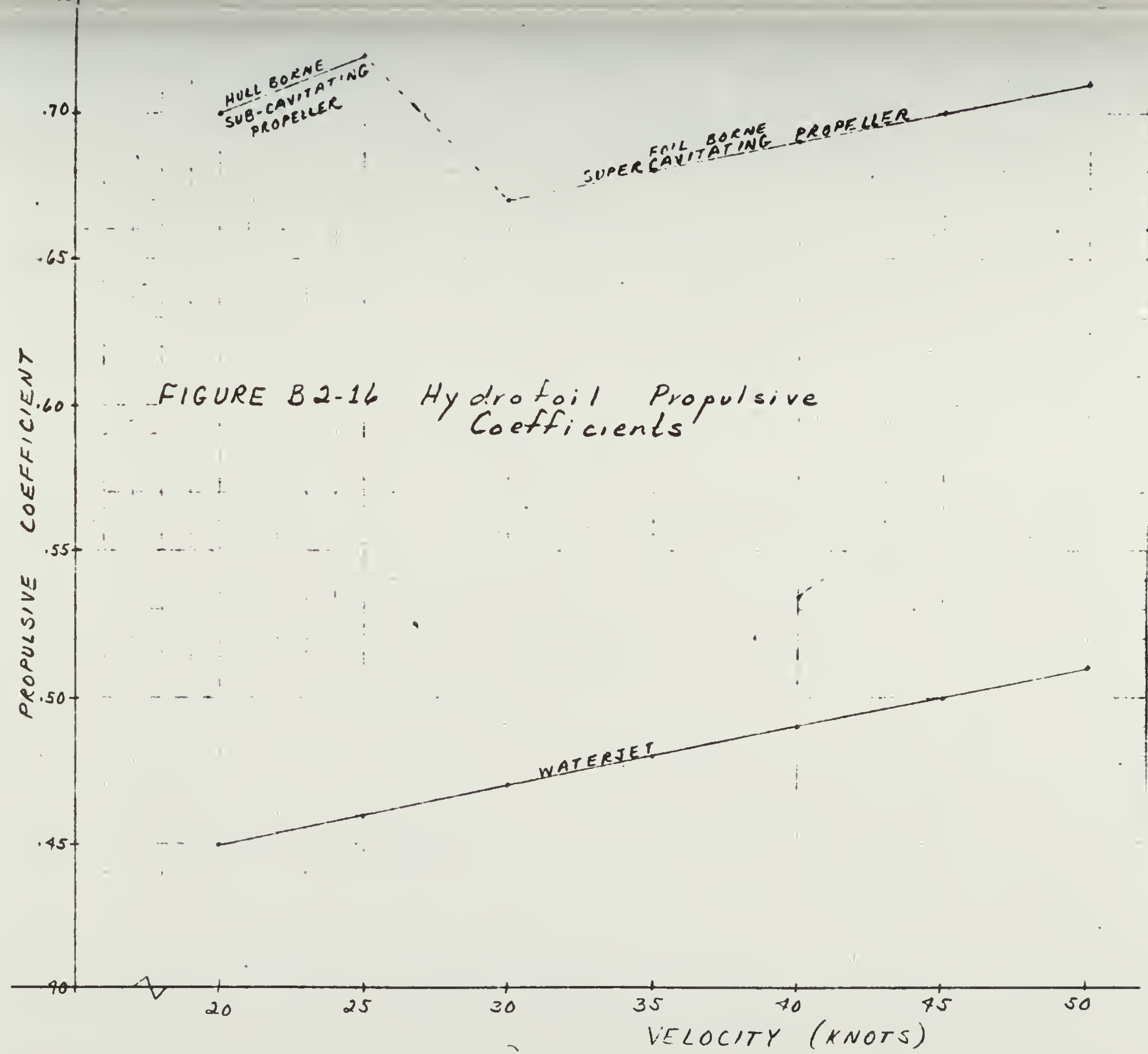


FIGURE B2-16 Hydrofoil Propulsive Coefficients

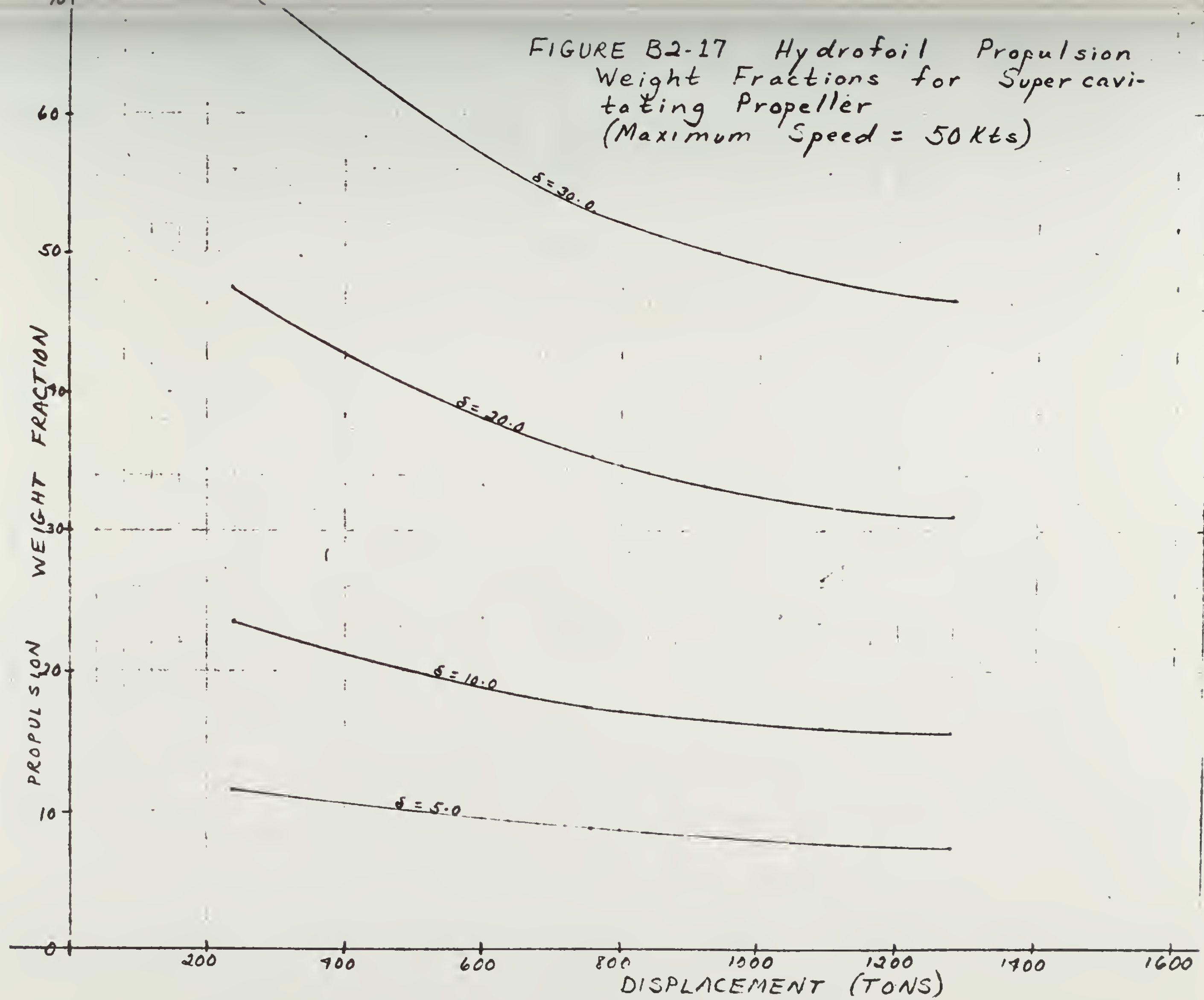


FIGURE B2-17 Hydrofoil Propulsion Weight Fractions for Supercavitating Propeller (Maximum Speed = 50 Kts)

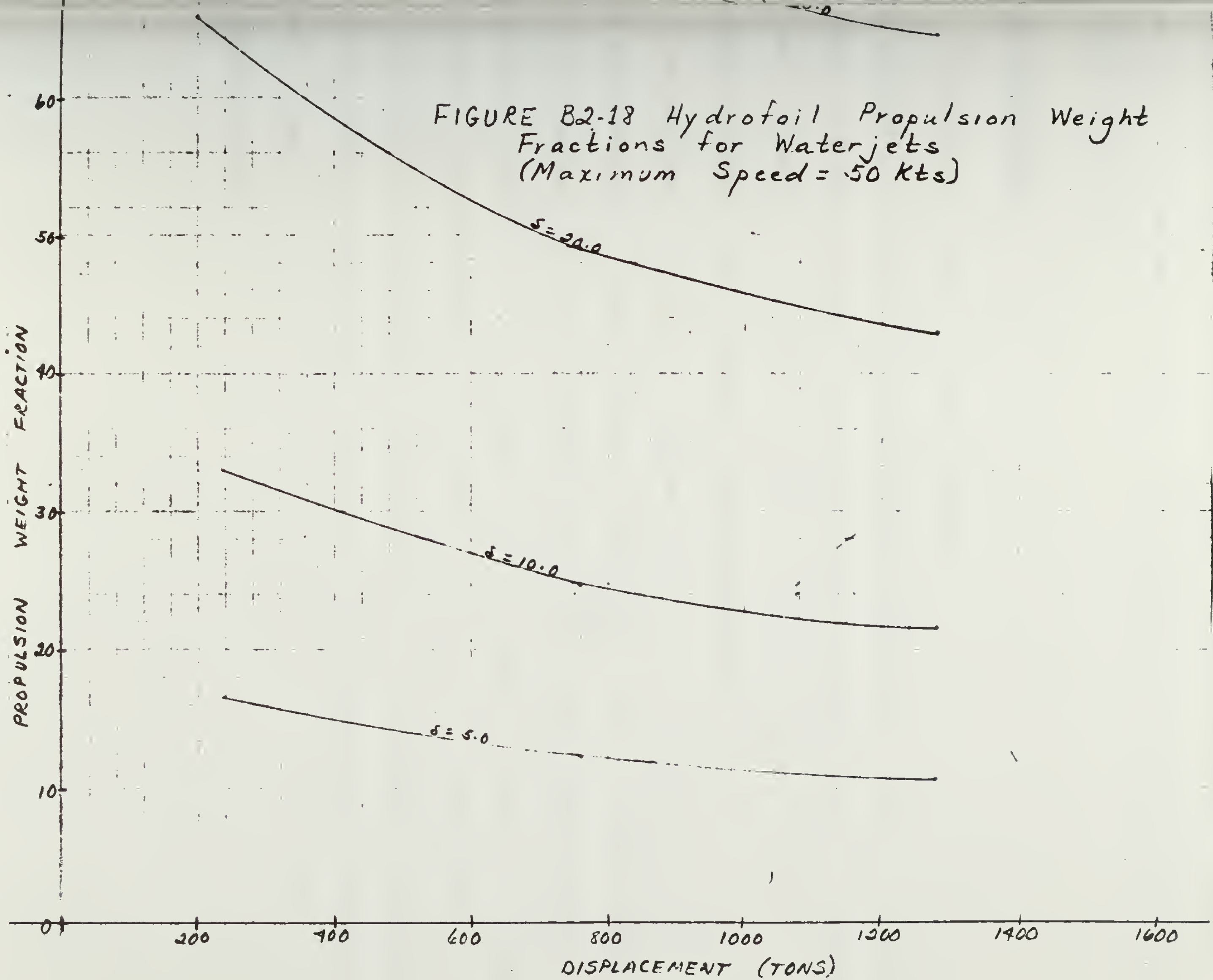


FIGURE B2-18 Hydrofoil Propulsion Weight Fractions for Waterjets (Maximum Speed = 50 kts)

However, Figure B2-19 reveals the most important parameter - range. For small hydrofoils such as the PHM, range is limited < 1000 nm. Only in the higher displacement hydrofoils (1300 tons) can even ranges approaching [illegible]000nm be attained.

B2.4 SES Details

The surface effect ship model was based on a $\ell_c/b_c = 2.0$, $P_c/l_c = 1.5$ SES analyzed in reference (R10). Utilizing these weight equations revealed a weight fraction breakdown for a typical supercavitating propeller SES as shown in Figure B2-10 (Propeller systems utilized rudders and waterjet systems utilized ventral fins for steering and stability.)

An analysis of the power requirements and fuel requirements for the SES again reveal the requirement for light-weight plants, or lower speeds. The lift-to-drag curve shown in Figure B2-21 was utilized along with the propulsive coefficient curve in Figure B2-22 to yield SHP versus Δ for supercavitating propellers (Figure B2-23) and for waterjets (Figure B2-24). It is these high shaft horsepowers that moreover drive the weight restrictions. As can be seen in Figure B2-25, ranges are indeed limited for a set cruise speed, although ranges can be more fully optimized by cruising at the highest L/D speed.

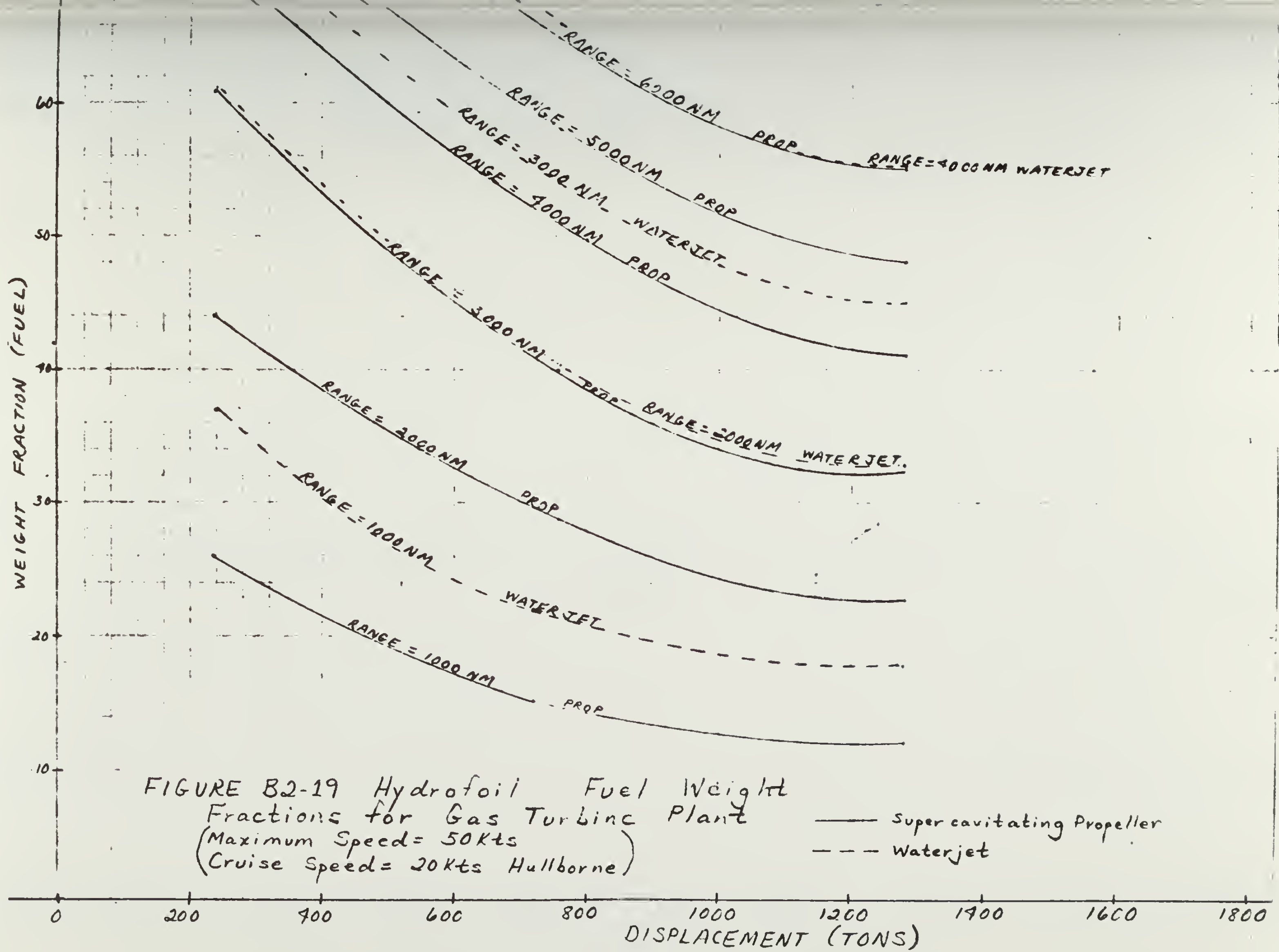


FIGURE B2-19 Hydrofoil Fuel Weight Fractions for Gas Turbine Plant
(Maximum Speed = 50 Kts
Cruise Speed = 20 Kts Hullborne)

FIGURE B2-20 Low ℓ_c/b_c SES Weight Fraction
(Supercavitating Propellers)
(Maximum Speed = 100 Kts)

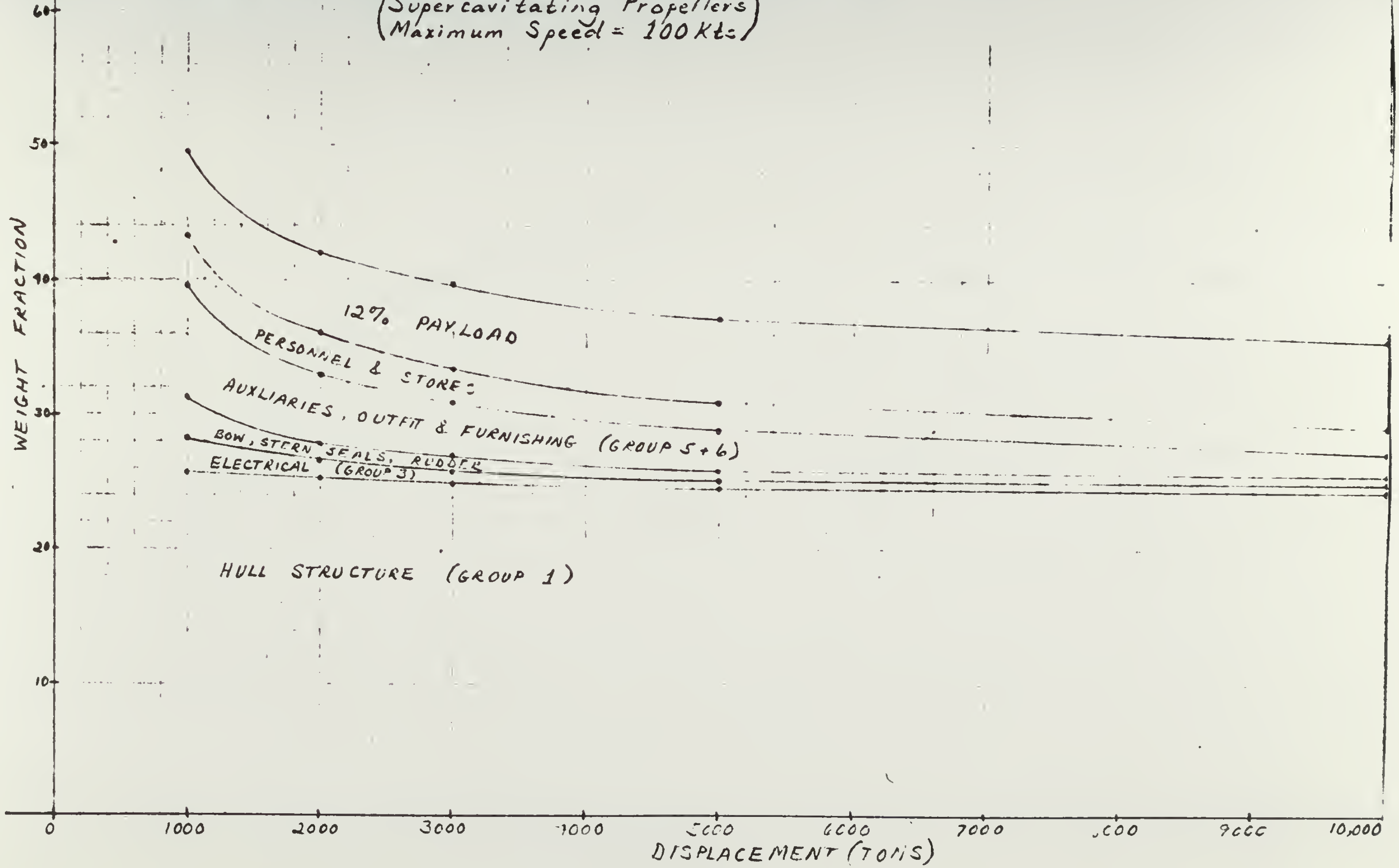
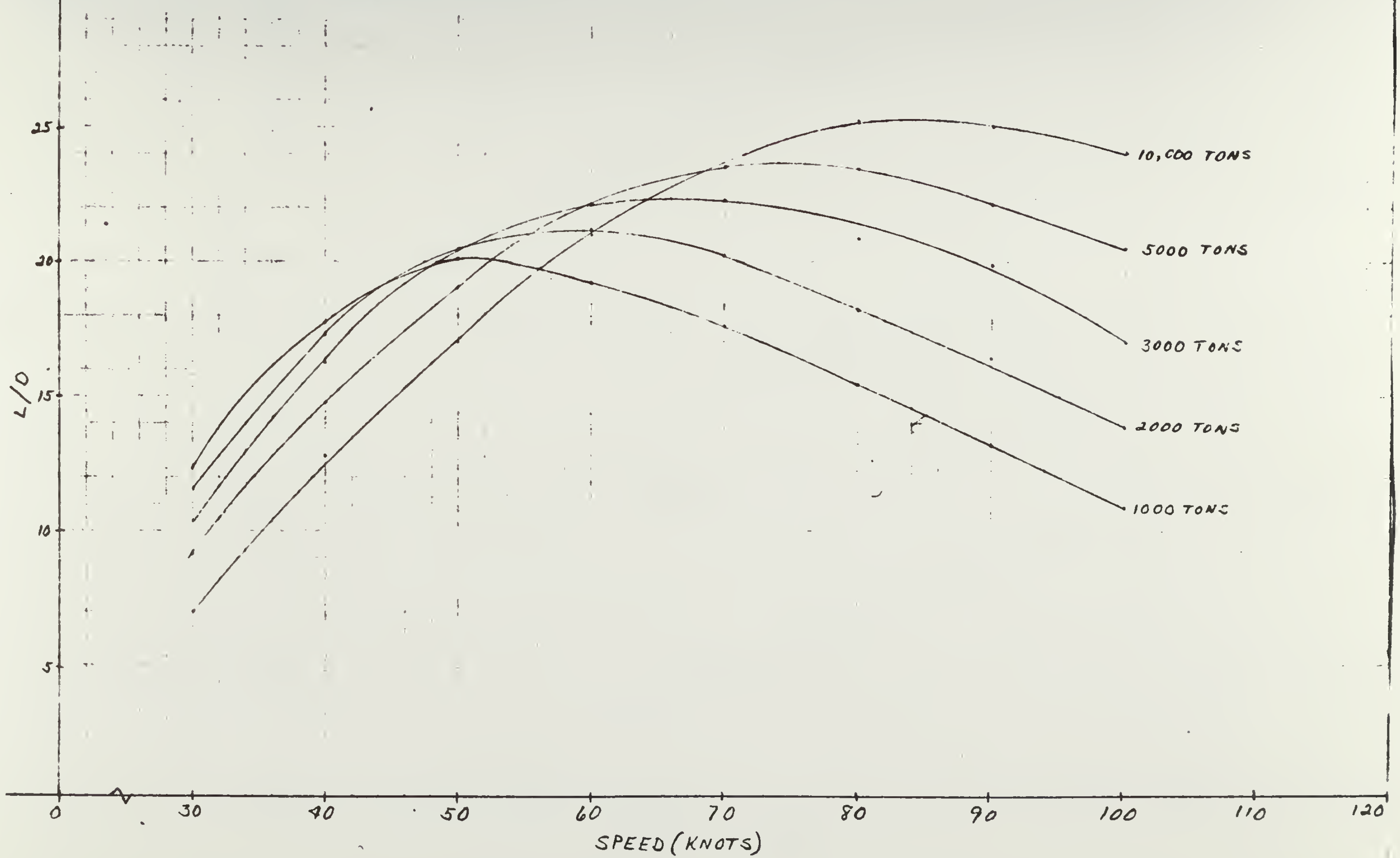


FIGURE B2-21 SES Lift-Drag Ratio Above the Hump (R10) $(\ell_c/b_c = 2.0 \quad P_c/\ell_c = 1.5)$



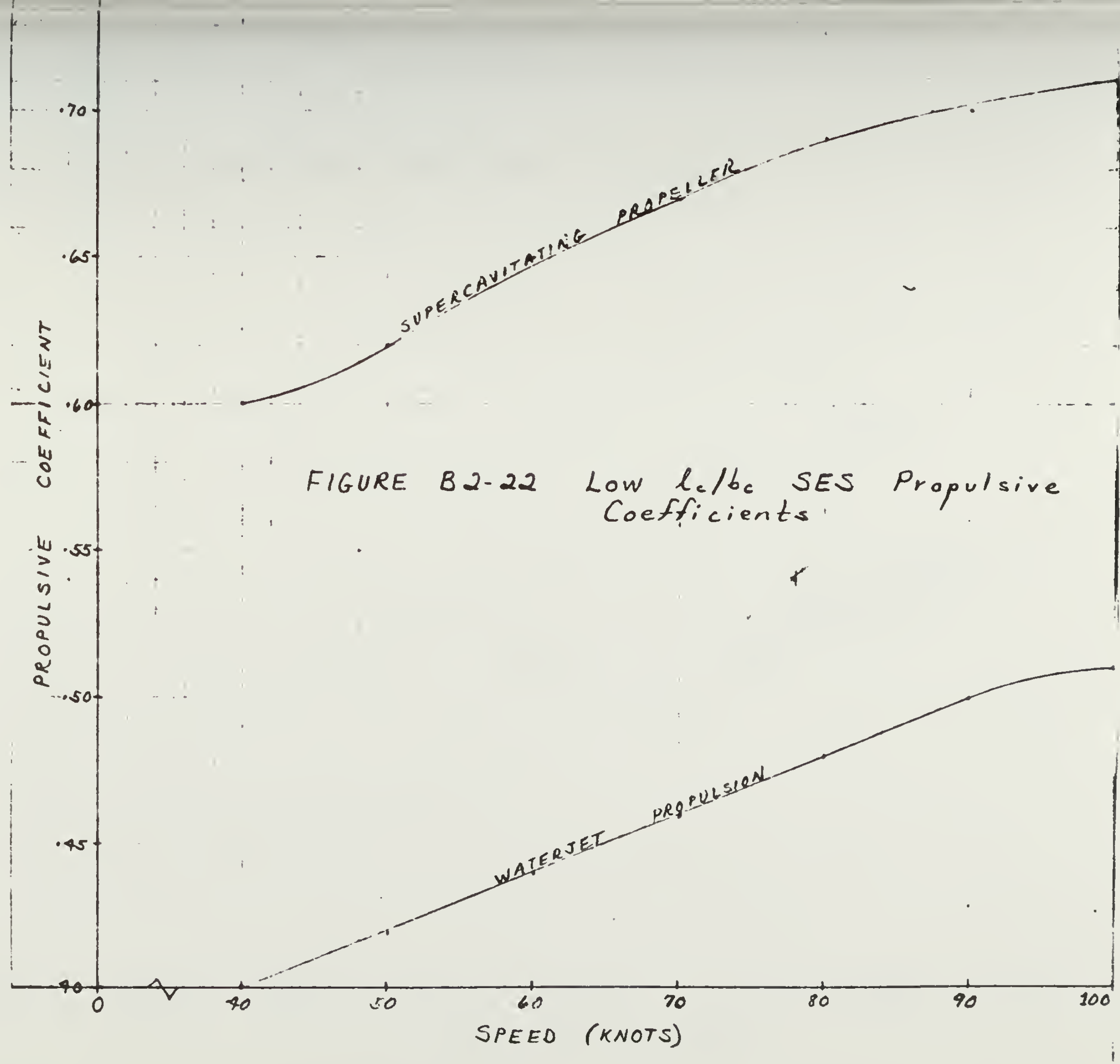


FIGURE B2-22 Low l_c/b_c SES Propulsive Coefficients

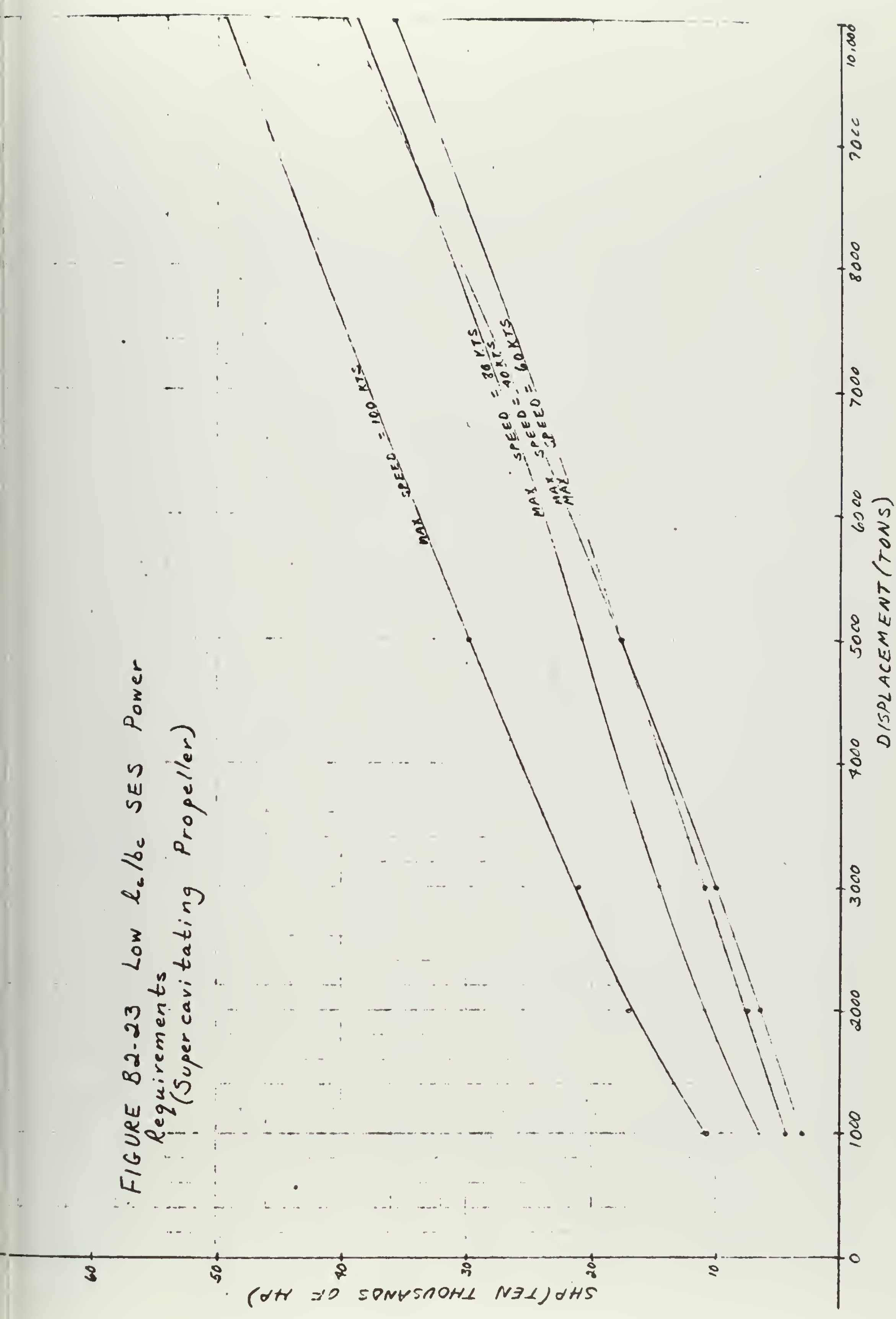


FIGURE B2-23 Low l_c/b_c SES Power Requirements (Supercavitating Propeller)

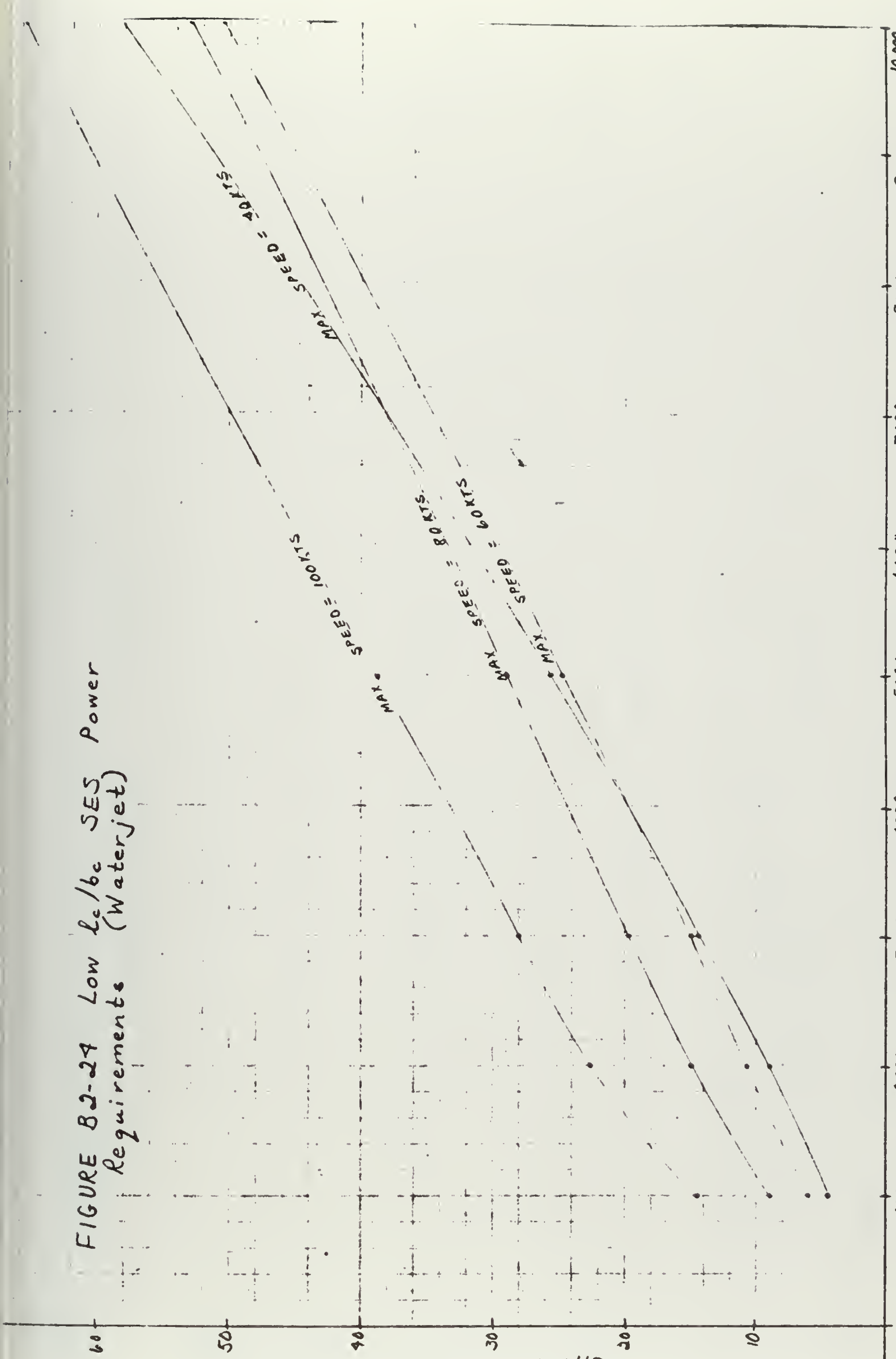


FIGURE B2-24 Low ℓ_c/b_c SES Power Requirements (Waterjet)

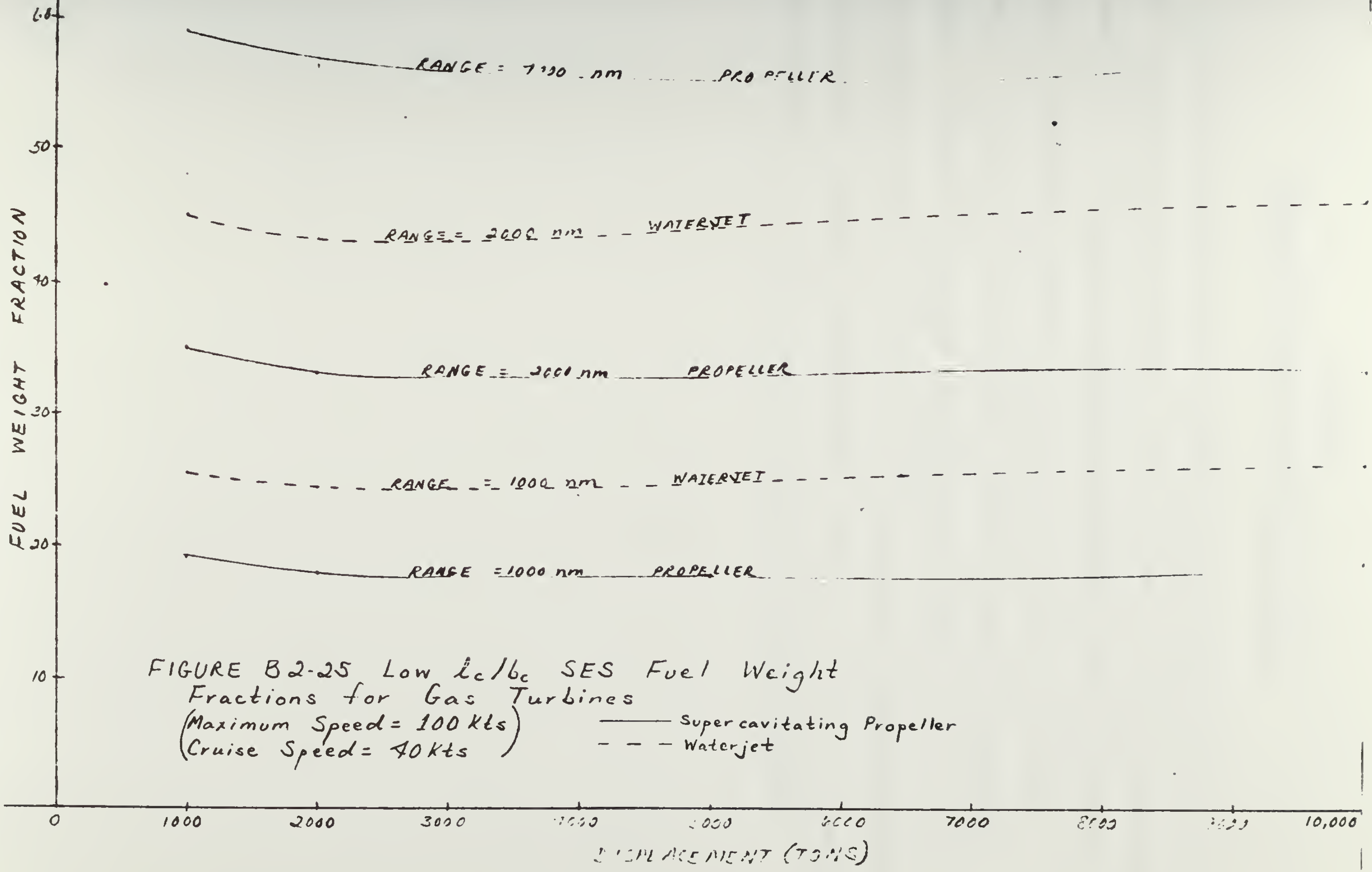


FIGURE B2-25 Low ℓ_c/b_c SES Fuel Weight Fractions for Gas Turbines
(Maximum Speed = 100 kts)
(Cruise Speed = 40 kts)

APPENDIX C

DETAILS OF NUCLEAR PROPULSION ANALYSIS

This Appendix details some of energy generation system design data, and weight breakdowns for the different nuclear systems. First in Section C1- the design data and weight breakdowns are detailed for the helium-cooled ; reactor, the sodium-cooled fast reactor, and the molten salt reactor ectively. In Section C4, the different compatible system combinations outlined. In Section C5, weight estimating relationships for the repair s and propulsion fluids, collision barriers, propulsion foundation increases, electrical power increases are determined. Section C6 details for the six r reactor systems, the overall specific propulsion weight breakdowns.

FIGURE C1-1 Compact Core Design Configuration

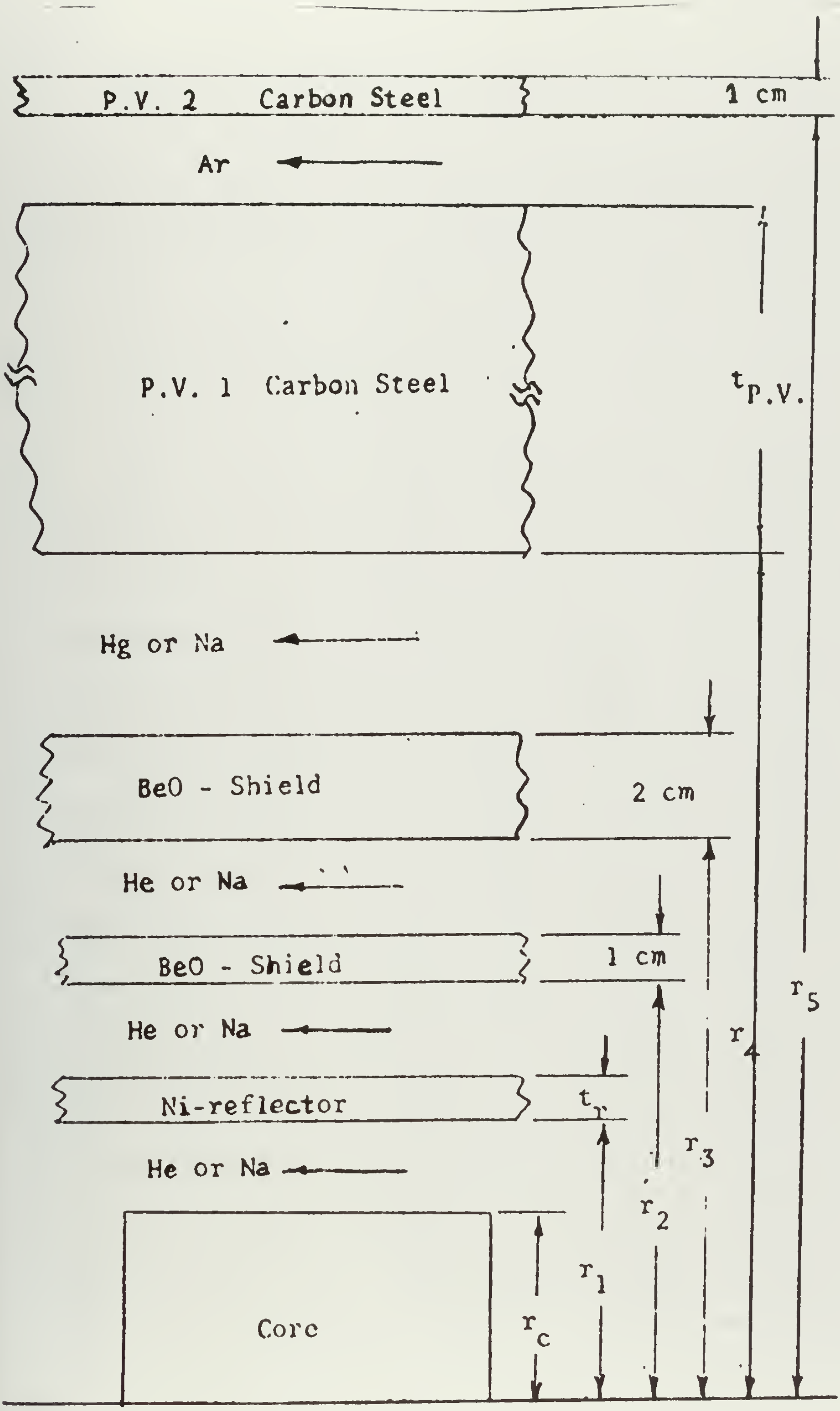


TABLE C1-1 Preliminary Design Data for He-Cooled Reactor (F3)

	Unit	100 MWt	200 MWt	.300 MWt	400 MWt
U^{235}	Vol%	15.337	11.927	10.236	9.264
U^{238}	Vol%	15.963	12.413	10.654	9.642
S. S.	Vol%	17.444	14.920	12.810	10.534
He	Vol%	49.500	60.740	66.300	69.500
Core Dia.	cm	70.5	90.5	105.5	118.0
Core Height	cm	70.5	90.5	105.5	118.0
Reflector Thickness	cm	1.50	2.55	3.25	3.00
Primary Shield Thick's	cm	5.0	5.0	5.0	5.0
Pressure Vessel Thick's	cm	12.0	12.0	12.0	12.0
Pressure Vessel Dia.	cm	121.6	147.6	164.0	176.0
Pressure Vessel Ht.	cm	232.2	291.7	354.0	368.0
Cont. Vessel Thick's	cm	1.0	1.0	1.0	1.0
Cont. Vessel Dia.	cm	123.6	149.6	166.0	178.0
Cont. Vessel Ht.	cm	234.2	293.7	356.0	370.0
Reactor Core Wt	ton	4.1	6.9	9.4	11.7
Reactor Vessel Wt	ton	5.30	8.4	11.0	13.2
Total Reactor Wt.	ton	10.1	17.0	23.0	28.0
Core Power Dens.	MW/L	0.363	0.344	0.325	0.310

TABLE C1-2 Average Core Neutron Flux for He-Cooled Reactor (F3)

	>1.35Mev	<1.35Mev	Total
100 MWt	1.61×10^{14}	5.86×10^{14}	7.47×10^{14}
200 MWt	2.08×10^{14}	7.54×10^{14}	9.62×10^{14}
300 MWt	2.30×10^{14}	8.32×10^{14}	1.06×10^{15}
400 MWt	2.40×10^{14}	8.76×10^{14}	1.12×10^{15}

TABLE C1-3 He-Cooled Fast Reactor Weights (F3)

		100 MWT	200 MWT	300 MWT	400 MWT
γ-Shield (Pb)		6.6	9.4	11.4	13.0
Neutron Shield (B_4C)	1	295.3	343.6	377.0	403.5
	2	242.6	287.9	338.6	354.9
	3	190.9	233.3	262.2	284.5
Reactor		10.1	17.0	23.0	28.0
Control and Safety System		2.1	3.5	4.7	5.8
Piping System	--	30.0	42.0	52.0	60.0
Misc. Wt.	--	20.0	28.0	35.0	40.0
Total Reactor Subsystem	1	364.1	443.5	503.1	550.3
	2	311.4	387.8	464.7	501.7
	3	259.7	333.2	388.3	431.3
Net Output Power in HP (η=0.42)		56,300	112,600	168,900	225,200
Power Density lb/HP	1	14.2	8.7	6.6	5.[illegible]
	2	12.2	7.6	6.1	4.9
	3	10.1	6.5	5.1	4.2

TABLE C2-1 (F3)

Preliminary Design Data for Na-Cooled Reactor
(U^{235}=15.582 Vol. %, U^{238}=16.218 Vol. %, S.S=19.5 Vol. %
Na=48.7 Vol. %)

	Unit	100 MWt	200 MWt	300 MWt	400 MWt
Core Dia.	cm	63.5	66.0	69.0	71.5
Core Height	cm	63.5	66.0	69.0	71.5
Reflector Thickness	cm	1.0	1.0	1.0	1.0
Primary Shield Thick's	cm	4.0	4.0	4.0	4.0
Pressure Vessel Thick's	cm	5.0	5.0	5.0	5.0
Pressure Vessel Dia.	cm	91.5	94.0	97.0	99.5
Pressure Vessel Ht.	cm	195.6	202.5	210.7	217.6
Cont. Vessel Thick's	cm	1.0	1.0	1.0	1.0
Cont. Vessel Dia.	cm	93.5	96.0	99.0	101.5
Cont. Vessel Ht.	cm	197.6	204.5	212.7	219.6
Reactor Core Wt.	ton	3.3	3.7	4.3	4.7
Reactor Vessel Wt.	ton	0.782	0.805	0.843	0.873
Total Reactor Wt.	ton	4.6	5.1	5.7	6.2
Core Power Dens.	MW/ℓ	0.497	0.886	1.163	1.395

TABLE C3-2 Average Core Neutron Flux for Na-cooled Reactor (F3)

	>1.35 Mev	<1.35 Mev	Total
100 MWt	2.85×10^{14}	1.03×10^{15}	1.32×10^{15}
200 MWt	4.00×10^{14}	1.45×10^{15}	1.85×10^{15}
300 MWt	5.30×10^{14}	1.90×10^{15}	2.43×10^{15}
400 MWt	6.30×10^{14}	2.28×10^{15}	2.91×10^{15}

TABLE C3-3 Preliminary Design of U-type Intermediate Hx for Na-cooled Reactor Coupled with Gas (He)-turbine Power Conversion System (F3)

Tube side: Ti=2000°R, Pi=100 psia, Tf=1260°R, Pf=95 psia, V=15 fps
Shell side: Ti=1200°R, Pi=750 psia, Tf=1950°R, Pf=740 psia, V=120 fps
Tube arrangement: OD=0.375, I.D.=0.305, Stainless Steel, Banks of finned tubes, triangular mesh distance = 1 in.

	Unit	100 MWt	200 MWt	300 MWt	400 MWt
No. of tubes		1051	2102	3153	4204
Overall heat transf. coef.	$\frac{BTU}{ft^2 hr\text{-}°F}$	331	331	331	331
Eff. heat transf. area	ft^2	13224	26448	39672	52896
Eff. tube length	ft	24	24	24	24
Estimated Hx O.D.	ft	4.50	6.33	7.83	9.00
Estimated Hx length	ft	18	18	18	18
Estimated Hx volume	ft^3	262.4	490.7	691.0	276.5
Estimated Hx weight	lb	33,500	52,800	70,000	86,000

TABLE C2-4 Preliminary Design of Intermediate Heat Exchanger for Na-cooled Reactor Coupled with LM-MHD Power Conversion System (F3)

	Unit	100 MWt		200 MWt		300 MWt		400 MWt	
		Na-Hx	He-Hx	Na-Hx	He-Hx	Na-Hx	He-Hx	Na-Hx	He-Hx
Tube size O.D.	in-gage	1.0-#16	.75-#16	1.0-#16	.75-#16	1.0-#16	.75-#16	1.0-#16	.75-#16
℄ - ℄ distance	in	1.25	1.00	1.25	1.00	1.25	1.00	1.25	1.00
log.-mean temp.	--	78.0	109.7	78.0	109.7	78.0	109.7	78.0	109.7
No. of tubes	--	509	1,002	1013	2,005	1,527	3008	2035	4010
Overall heat transf. coef.	$\frac{BTU}{ft^2\text{-hr-}°F}$	2633	331	2633	331	2,633	331	2,633	331
Eff. heat transfer area	ft^2	1024	3610.9	2048	722.15	3072	10332.6	4096.5	14443.5
Eff. tube length	ft	8.84	18.34	8.84	18.34	8.84	18.34	8.84	18.34
Estimated Hx O.D.	ft	3.0	3.00	4.00	4.58	4.83	5.58	5.67	6.25
Estimated Hx length	ft	14.84	24.34	14.84	24.34	14.84	24.34	14.84	24.34
Estimated Hx volume	ft^3	104.6	417	186.5	936.7	271.9	623 x 2	374	936.7x2
Estimated Hx weight	lb	9072	40440	13934	74930	17,694	106600	21863	136600

TABLE C2-5 Sodium-cooled Reactor Subsystem Performance (F3)

		100 MWT	200 MWT	300 MWT	400 MWT
γ-Shield (Pb)		6.0	6.3	6.7	7.0
Neutron shield (B_4C) (Mton)	1	207.2	211.1	217.1	222.0
	2	167.9	173.4	177.6	182.0
	3	130.0	134.1	139.0	144.0
Reactor (Mton)		4.6	5.1	5.7	6.2
Control and Safety System (Mton)		2.1	3.5	4.7	5.8
Heat Exchanger (Mton)		15.2	24.0	31.8	39.1
MHD HXs * (Mton)		22.8	40.4	56.5	72.0
Reactor Pump (Mton)	~	1.0	2.0	3.0	4.0
Piping System (Mton)	~	40.0	56.6	69.3	80.0
HX Shield and Misc. Wt. (Mton)	~	40.0	56.6	69.3	80.0
Total Reactor Subsystem Weight (Mton)	1	316.1 323.7 *	365.2 381.6 *	407.6 432.3 *	444.1 477.[illegible] *
	2	276.8 284.4 *	327.5 343.9 *	368.1 392.8 *	404.1 437.[illegible] *
	3	238.9 246.5 *	288.2 304.6 *	329.5 354.2*	366.[illegible] 398.[illegible] *
Net Output Power (η=0.41) HP		55,000	110,000	164,900	219,800
Power Density lb/HP	1	12.64 12.95 *	7.30 7.63 *	5.44 5.77 *	4.45 4.77 *
	2	11.07 11.38 *	6.55 6.88 *	4.91 5.24 *	4.01 4.37 *
	3	9.56 9.86 *	5.76 6.09 *	4.40 4.73 *	3.64 3.90 *

*Reactor subsystem performance for a two-phase liquid-metal MHD conversion system.

Pump, Shield Assembly, and Boiler for a Series of MSR Marine Power Plants (R2)

Reactor power, Mw(t)	25	50	100	200	400
Reactor					
Core diameter, in.	30	36	45	60	76
Reflector thickness, in.	24	24	24	24	24
Shell ID, in.	78	86	96	108	124
Shell thickness, in.	0.5	0.5	0.5	0.5	0.6
Shell weight, lb	2700	3300	4100	5200	6800
Graphite weight, lb	14,400	19,300	26,800	38,200	58,000
Total reactor	17,100	22,600	30,900	43,400	64,800
Fuel volume, ft^3					
Reactor core	1.76	3.53	7	14	28
Heat exchanger	3.5	7.0	14	28	56
Connecting passages	2.5	5.0	10	20	40
Total	7.8	15.5	31	62	124
Fuel weight, lb	1,600	3,100	6,200	12,400	25,000
Heat Exchanger					
Number of tubes	110	220	440	880	1760
Weight of tubes, lb	180	360	720	1440	2880
Weight of shell, lb	250	350	700	1000	2800
Fuel flow rate, gpm	105	210	420	840	1680
Pump weight, lb	400	500	700	1000	1600
Pump and heat exchanger weight, lb.	830	1210	2120	3840	7280
Shield					
Pb thickness	13	13	13	13	13
Pb ID, in.	92	100	110	122	138
Pb OD, in.	118	126	136	148	164
Pb weight, lb	180,000	210,000	246,000	300,000	370,000
H_2O thickness, in.	30	30	30	30	30

Table C3-1 (Continued)

H_2O ID, in.	82	90	100	112	128
H_2O OD, in.	168	176	186	198	214
H_2O weight, lb (no corr. for Pb)	80,000	90,000	100,000	120,000	145,000
H_2O weight, lb (corr. for Pb)	64,000	71,000	78,000	93,000	112,000
Structure, lb (10%)	25,000	28,000	32,000	39,000	48,000
Total shield	269,000	309,000	356,000	432,000	530,000
Total reactor, heat exchanger, pump, and shield assembly	288,500	336,000	395,000	492,000	627,000
Molten salt-to-steam boiler (1000 psia, 1000°F)					
Number of units	2	2	2	4	4
Number of tubes/unit	263	525	1050	1050	2100
Outer tube OD, in.	5/8	5/8	5/8	5/8	5/8
Tube length, ft	20	20	20	20	20
Shell ID, in.	12.5	17.7	25	25	35
Shell thickness, in.	0.25	0.25	0.25	0.25	0.375
Shell weight, lb (per unit)	760	1100	1500	1500	3200
Tube weight, lb	2630	5250	10,500	10,500	21,000
Total boiler weight, lb (all units)	7000	13,000	25,000	50,000	100,000
Total weight including boiler, lb	300,000	350,000	430,000	560,000	760,000

ABLE C4-1 Compatible Pressurized Water Reactor Systems

Matrix #	η cycle	Shaft Horsepower	δ_o $\left(\frac{lbm}{SHP}\right)$
1 NPWR (Existing)	0.24	60,000	118.0
1 NPWR (Advances)	0.24	60,000	90.2
2 NPWR (Existing)	0.24	60,000	119.0
12 NPWR (Advances)	0.24	60,000	91.1
13 NPWR (Existing)	0.24	60,000	110.4
14 NPWR (Existing)	0.24	60,000	110.7
5 NPWR (Existing)	0.24	60,000	112.8
6 NPWR (Existing)	0.24	60,000	112.3
17 NPWR (Existing)	0.24	60,000	109.0
11 UNIMOD (Existing)	0.24	30,000	84.3
11 UNIMOD (Advances)	0.24	30,000	58.3
11 UNIMOD (Existing)	0.24	60,000	73.6
11 UNIMOD (Advances)	0.24	60,000	47.8
12 UNIMOD (Advances)	0.24	30,000	59.8
12 UNIMOD (Advances)	0.24	60,000	48.6
13 UNIMOD (Advances)	0.24	30,000	58.7
13 UNIMOD (Advances)	0.24	60,000	49.0
14 UNIMOD (Advances)	0.24	30,000	59.8
114 UNIMOD (Advances)	0.24	60,000	49.3
115 UNIMOD (Advances)	0.24	30,000	60.9
115 UNIMOD (Advances)	0.24	60,000	51.1
116 UNIMOD (Advances)	0.24	30,000	60.5
116 UNIMOD (Advances)	0.24	60,000	50.7
117 UNIMOD (Advances)	0.24	30,000	49.4
117 UNIMOD (Advances)	0.24	60,000	48.9
11 CNSG (Existing)	0.24	70,000	98.4
11 CNSG (Advances)	0.24	70,000	71.4
12 CNSG (Advances)	0.24	70,000	72.7
113 CNSG (Advances)	0.24	70,000	73.4
114 CNSG (Advances)	0.24	70,000	73.5
15 CNSG (Advances)	0.24	70,000	75.6
16 CNSG (Advances)	0.24	70,000	75.1
17 CNSG (Advances)	0.24	70,000	73.9

Table C4-2 Compatible He Cooled Fast Reactor Systems

Matrix #	η_{cycle}	Shaft Horse power	S_o $\left(\frac{lbm}{SHP}\right)$
211	0.35		
212	0.35		
213	0.35		
214	0.35	Not Examined	
215	0.35		
246	0.40		
247	0.40		
51 Direct Cycle	0.41	54,900 — 219,500	27.6 — 18.3
52 Direct Cycle	0.41	54,900 — 219,500	28.4 — 19.1
53 Direct Cycle	0.41	54,900 — 219,500	28.7 — 21.7
54 Direct Cycle	0.41	54,900 — 219,500	29.1 — 19.8
55 Direct Cycle	0.41	54,900 — 219,500	30.7 — 23.7
51 Indirect Cycle	0.29		
52 Indirect Cycle	0.29		
53 Indirect Cycle	0.29		
54 Indirect Cycle	0.29	Not Examined	
55 Indirect Cycle	0.29		
266	0.42		
267	0.42		

ABLE C4-3 ompatible Na- Cooled Fast Reactor Systems

Matrix #	η cycle	Shaft Horsepower	S_0 ($\frac{lbm.}{SHP}$)
311	Not Examined		
312			
313			
314			
315			
346	0.41	55,000 — 219,800	30.0 — 24.0
347	0.41	55,000 — 219,800	28.3 — 20.0
351	0.41	55,000 — 219,800	24.4 — 16.1
352	0.41	55,000 — 219,800	25.3 — 17.0
353	0.41	55,000 — 219,800	25.6 — 18.2
354	0.41	55,000 — 219,800	26.0 — 17.7
355	0.41	55,000 — 219,800	27.6 — 21.6
366	0.42	55,000 — 219,800	30.5 — 23.9
367	0.42	55,000 — 219,800	28.8 — 19.9

TABLE C4-4 Compatible Molten Salt Reactor Systems

Matrix #	η_{cycle}	Shaft Horsepower	δ_o $\left(\frac{lbm}{SHP}\right)$
411	0.35	11,700 — 187,400	51.4 — 28.7
412	0.35	11,700 — 187,400	52.3 — 29.6
413	0.35	11,700 — 187,400	51.3 — 31.8
414	0.35	11,700 — 187,400	53.0 — 30.3
415	0.35	11,700 — 187,400	53.3 — 34.0
451	Not Examined		
452			
453			
454			
455			

BLE C4-5 Compatible Water Moderated He Cooled Reactor Systems

Matrix #	η_{cycle}	Shaft Horsepower	S_o ($\frac{lbm}{SHP}$)
511	0.337	27,300	64.3
512	0.337	27,300	65.1
513	0.337	27,300	64.6
514	0.337	27,300	65.8
515	0.337	27,300	66.8
516			
517			
1 Direct Cycle			
2 Direct Cycle			
3 Direct Cycle			
4 Direct Cycle			
5 Direct Cycle	Not Examined		
1 Indirect Cycle			
2 Indirect Cycle			
3 Indirect Cycle			
4 Indirect Cycle			
5 Indirect Cycle			
566			
567			

TABLE C4-6 Graphite Moderated Gas Cooled Epithermal Reactor Systems

Matrix #	η_{CYCLE}	Shaft Horse power	$\delta_o \left(\frac{lbm}{SHP}\right)$
611			
612			
613			
614			
615			
646	Not Examined		
647			
51 Direct Cycle			
52 Direct Cycle			
53 Direct Cycle			
54 Direct Cycle			
55 Direct Cycle			
56 Direct Cycle	0.35	25,000 — 400,000	41.1 — 18.6
57 Direct Cycle	0.35	25,000 — 400,000	40.2 — 13.0
51 Indirect Cycle			
52 Indirect Cycle			
53 Indirect Cycle			
54 Indirect Cycle			
55 Indirect Cycle	Not Examined		
56 Indirect Cycle			
57 Indirect Cycle			
666			
667			

C5 WEIGHT ESTIMATING RELATIONSHIPS

To estimate the repair parts and propulsion fluid weight requirements r many of the nuclear systems, representative specific weights for various nventional fossil-fueled ships were analyzed and a factor of three applied ice nuclear ships operate at endurances about three times that of fossil-led ships. This translated into 6.1 lbm/SHP for repair parts and propulsion rating fluids.

Estimating the weight necessary for collision/structural bulkheads was ided into two different relationships. For conventional protection systems h as installed in the SS Savannah, 250 - 300 tons were required depending the actual plant length. This protection system was designed based on a babalistic impact energy study summarized in (R8).

However, a more exotic collision system was also estimated based on 2), an empirical peripheral collision protection structure study for an tic SES. Protection schemes included such energy absorption mechanisms collapsible tubes, automotive type air bags, fluid shock absorbers, and m core sandwich panels. Figure C5-1 shows the energy absorption capability several such components shown in decreasing capability from the most ficient (buckling tubes) to the least efficient (foam core sandwich panels). ure C5-2 summarizes the weight for a 500 ton Arctic SES utilizing buckling pod tubes. Assuming a velocity of impact for the impacting ship (most high rgy ships are $\leq$ 30 knots) and eight feet of collision barrier either side the containment vessel, Figure C5-3 was generated.

It should be noted that numerous high impact studies were done for the plane nuclear power (ANP) program which proved that light-weight collision tection can be provided for high velocity impacts (400 ft/sec).

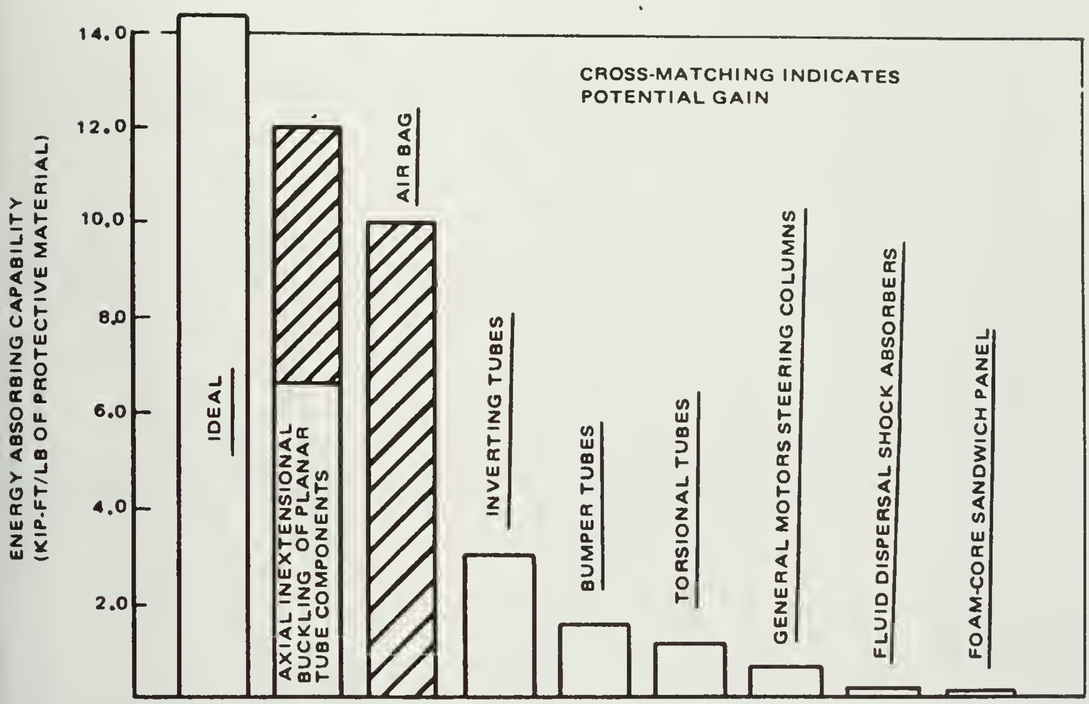


FIGURE CS-1 *Specific Energy Absorptions for Various Components* (G-12)

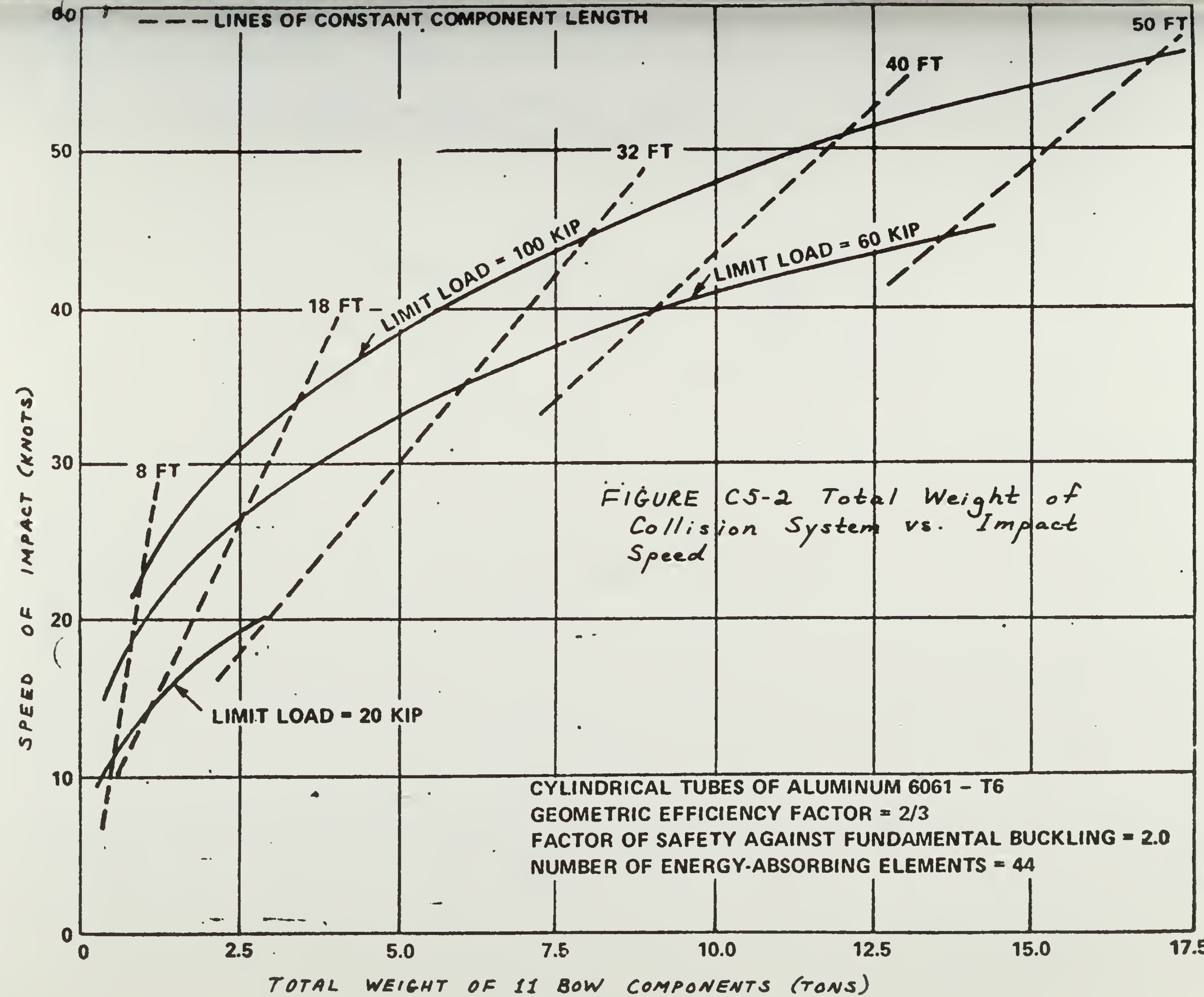


FIGURE C5-2 Total Weight of Collision System vs. Impact Speed

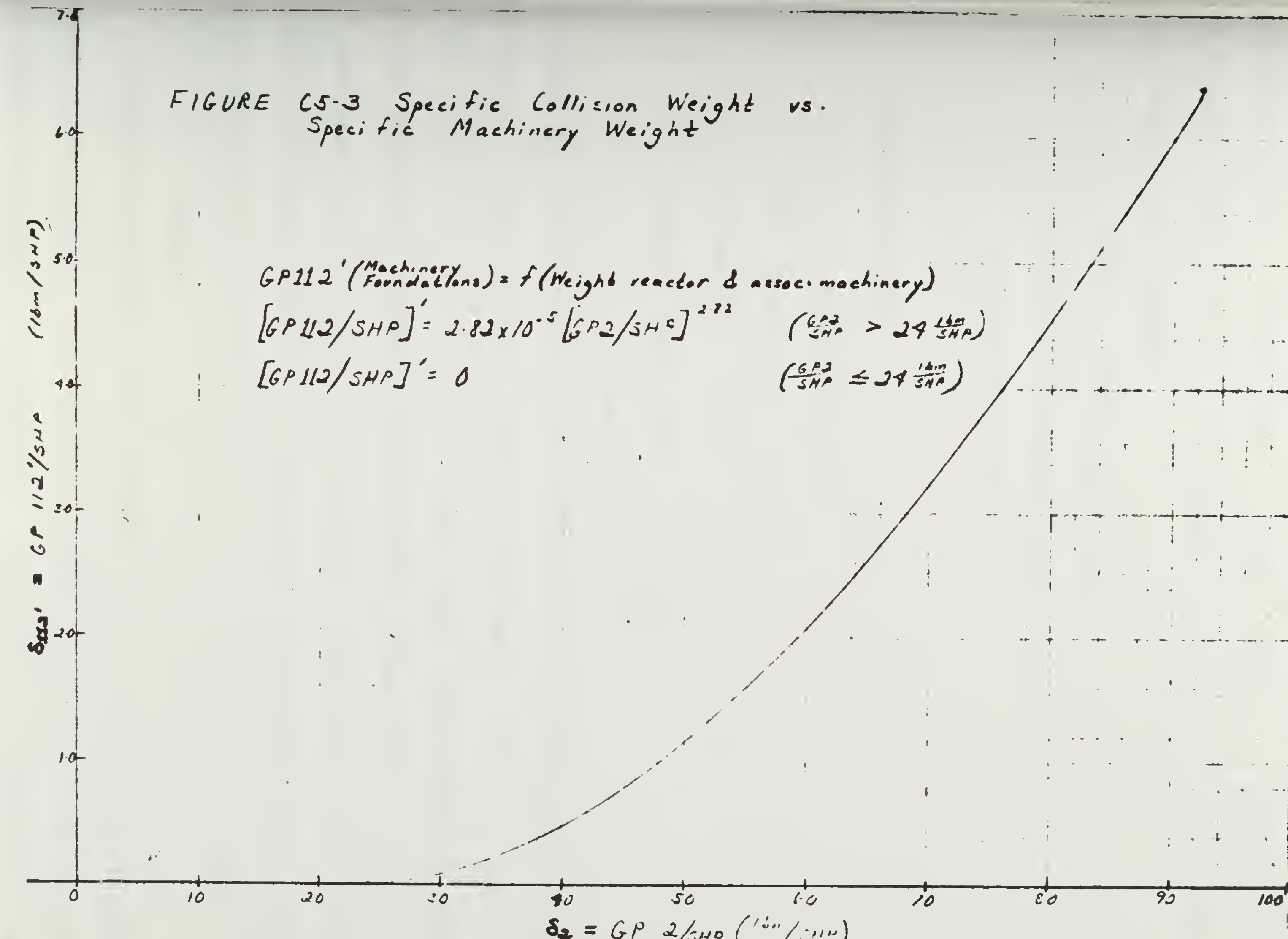


FIGURE C5-3 Specific Collision Weight vs. Specific Machinery Weight

To determine the increased weight necessary for foundation weight to ructurally support the point loads of nuclear reactors, a study was made the various factors affecting foundation weights. The factors causing dnamic loads are as follows:

1. Vibration of the ship structure
2. Vibration of the mounted unit
3. Variable thrust or torque
4. Shock

The factors causing static loads are as follows:

1. Deadweight of component
2. Ship motions in a seaway
3. Gyroscopic reactions of rotating machinery
4. Thermal deflections
5. Steady state reactions

en examining several similar nuclear ships and fossil-fueled ships revealed at there were indeed weight increases as δ_2 increased. The higher δ_2 forces eater weight increases than for the lower plants since one of the requirents for the nuclear systems is that the primary components be supported on e common structure so as to minimize opposing motions due to the ship orking" in the sea. Therefore, higher δ_2 imply greater containment length stems and more weight for the structural bed. Figure C5-4 describes the sults of this analysis.

Lastly, to account for the increased weight due to electrical machinery support the propulsion plant, similar nuclear and fossil-fueled ships were ain compared to determine a difference. Furthermore, an estimate was made r superconducting electrical systems as delineated in Chapter 4.

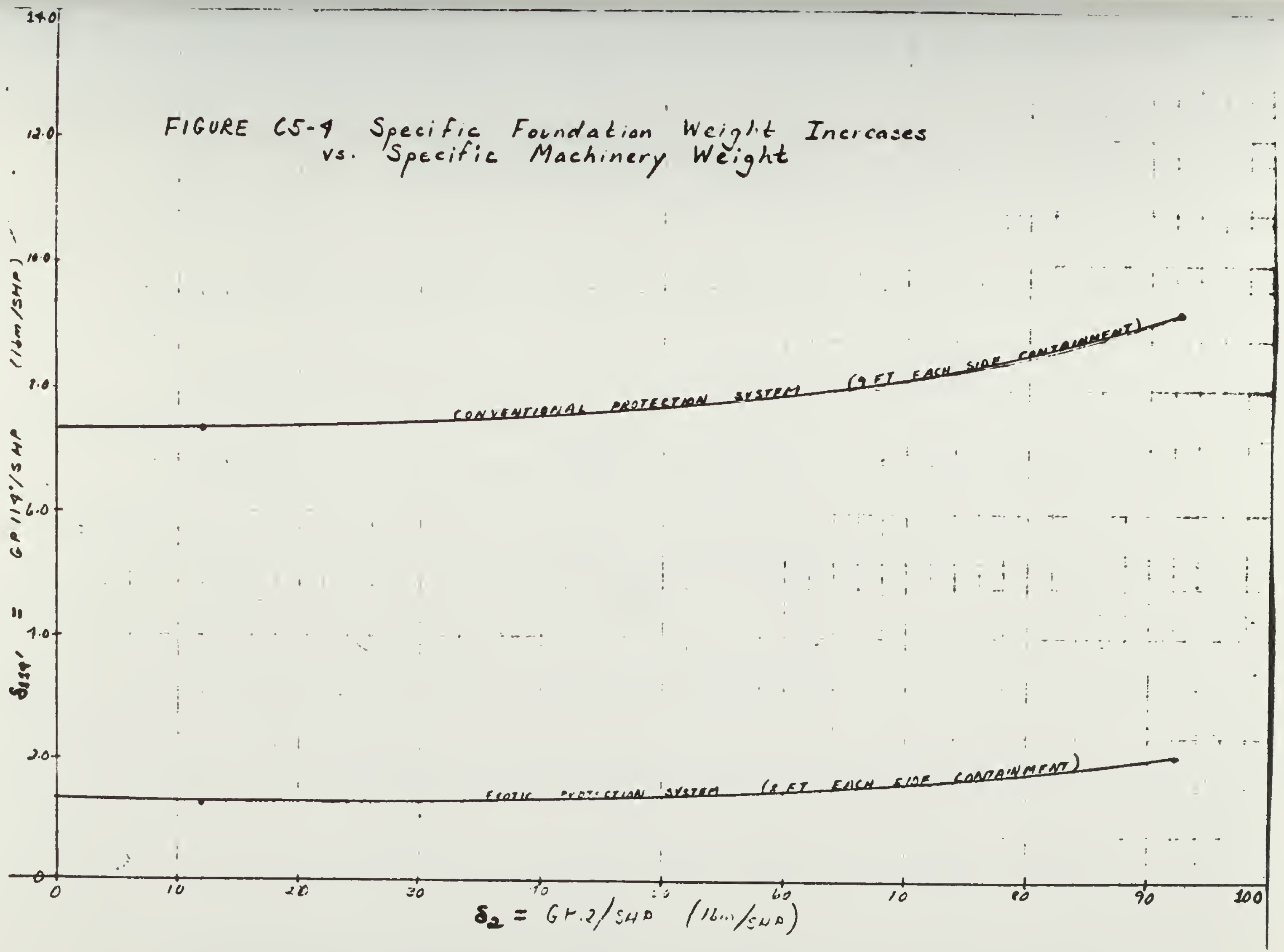


FIGURE C5-4 Specific Foundation Weight Increases vs. Specific Machinery Weight

TABLE C6-1 δ_o Weight Breakdown for Pressurized Water Reactor Systems

Shaft Horsepower	Matrix #	δ_{21}	δ_{22}	δ_{23}	δ_{29}	$\delta_{112'}$	$\delta_{114'}$	$\delta_{3'}$	δ_o
60,000	111 NPWR Existing	60.5	14.1	9.2	6.1	5.8	9.0	13.2	118.0
60,000	111 NPWR Advances	60.5	14.1	1.8	6.1	4.6	2.0	1.1	90.2
60,000	112 NPWR Existing	60.5	14.1	10.0	6.1	6.0	9.1	13.2	119.0
60,000	112 NPWR Advances	60.5	14.1	2.6	6.1	4.7	2.0	1.1	91.1
60,000	113 NPWR Existing	60.5	14.1	3.0	6.1	4.8	8.7	13.2	110.4
60,000	114 NPWR Existing	60.5	14.1	3.3	6.1	4.8	8.7	13.2	110.7
60,000	115 NPWR Existing	60.5	14.1	5.0	6.1	5.1	8.8	13.2	112.8
60,000	116 NPWR Existing	60.5	14.1	4.6	6.1	5.0	8.8	13.2	112.3
60,000	117 NPWR Existing	60.5	14.1	1.9	6.1	4.6	8.6	13.2	109.0
30,000	111 UNIMOD Existing	32.1	14.1	9.2	6.1	2.1	7.5	13.2	[illegible]4.3
30,000	111 UNIMOD Advances	32.1	14.1	1.9	6.1	1.5	1.5	1.1	58.3
60,000	111 UNIMOD Existing	22.1	14.1	9.2	6.1	1.3	7.3	13.2	73.6
60,000	111 UNIMOD Advances	22.1	14.1	1.8	6.1	0.9	1.4	1.1	47.8
30,000	112 UNIMOD Advances	32.1	14.1	2.6	6.1	2.3	1.5	1.1	59.8
60,000	112 UNIMOD Advances	22.1	14.1	2.6	6.1	0.9	1.4	1.1	48.6
30,000	113 UNIMOD Advances	32.1	14.1	2.3	6.1	1.5	1.5	1.1	58.7
60,000	113 UNIMOD Advances	22.1	14.1	3.0	6.1	0.9	1.4	1.1	49.0
30,000	114 UNIMOD Advances	32.1	14.1	3.3	6.1	1.6	1.5	1.1	59.8
60,000	114 UNIMOD Advances	22.1	14.1	3.3	6.1	0.9	1.4	1.1	49.3
30,000	115 UNIMOD Advances	32.1	14.1	4.3	6.1	1.7	1.5	1.1	60.9
60,000	115 UNIMOD Advances	22.1	14.1	5.0	6.1	1.0	1.4	1.1	51.1
30,000	116 UNIMOD Advances	32.1	14.1	3.9	6.1	1.7	1.5	1.1	60.5
60,000	116 UNIMOD Advances	22.1	14.1	4.6	6.1	1.0	1.4	1.1	50.7
30,000	117 UNIMOD Advances	32.1	14.1	2.9	6.1	1.5	1.4	1.1	49.4
60,000	117 UNIMOD Advances	22.1	14.1	2.9	6.1	0.9	1.4	1.1	48.9
70,000	111 CNSG Existing	44.2	14.1	9.2	6.1	3.4	8.2	13.2	98.4
70,000	111 CNSG Advances	44.2	14.1	1.8	6.1	2.5	1.6	1.1	71.4
70,000	112 CNSG Advances	44.2	14.1	2.6	6.1	2.6	1.6	1.1	72.7
70,000	113 CNSG Advances	44.2	14.1	3.2	6.1	2.7	1.6	1.1	73.9
70,000	114 CNSG Advances	44.2	14.1	3.3	6.1	2.7	1.6	1.1	73.5
70,000	115 CNSG Advances	44.2	14.1	5.2	6.1	2.9	1.6	1.1	75.6
70,000	116 CNSG Advances	44.2	14.1	4.8	6.1	2.8	1.6	1.1	75.1
70,000	117 CNSG Advances	44.2	14.1	2.8	6.1	2.6	1.6	1.1	73.9

TABLE C6-2 δ_0 Weight breakdown for He-Cooled Fast Reactor Systems

Shaft horsepower	Matrix #	δ_{21}	δ_{22}	δ_{23}	δ_{29}	$\delta_{112'}$	$\delta_{114'}$	$\delta_{3'}$	δ_0
4,900	251 Direct Cycle	14.6	2.5	1.8	6.1	0.2	1.3	1.1	27.6
4,900	252 Direct Cycle	14.6	2.5	2.6	6.1	0.2	1.3	1.1	28.4
54,900	253 Direct Cycle	14.6	2.5	2.9	6.1	0.2	1.3	1.1	28.7
54,900	254 Direct Cycle	14.6	2.5	3.3	6.1	0.2	1.3	0.0	29.1
54,900	255 Direct Cycle	14.6	2.5	4.9	6.1	0.2	1.3	0.0	30.7
09,800	251 Direct Cycle	8.9	2.5	1.8	6.1	0.1	1.3	1.1	21.8
09,800	252 Direct Cycle	8.9	2.5	2.6	6.1	0.1	1.3	1.1	22.6
09,800	253 Direct Cycle	8.9	2.5	3.8	6.1	0.1	1.3	1.1	23.8
109,800	254 Direct Cycle	8.9	2.5	3.3	6.1	0.1	1.3	0.0	23.3
109,800	255 Direct Cycle	8.9	2.5	5.9	6.1	0.1	1.3	0.0	25.9
164,700	251 Direct Cycle	6.8	2.5	1.8	6.1	0.1	1.3	1.1	19.7
64,700	252 Direct Cycle	6.8	2.5	2.6	6.1	0.1	1.3	1.1	20.5
164,700	253 Direct Cycle	6.8	2.5	4.6	6.1	0.1	1.3	1.1	22.5
64,700	254 Direct Cycle	6.8	2.5	3.3	6.1	0.1	1.3	0.0	21.2
164,700	255 Direct Cycle	6.8	2.5	6.6	6.1	0.1	1.3	0.0	24.5
219,500	251 Direct Cycle	5.5	2.5	1.8	6.1	0.0	1.3	1.1	18.3
219,500	252 Direct Cycle	5.5	2.5	2.6	6.1	0.0	1.3	1.1	19.1
219,500	253 Direct Cycle	5.5	2.5	5.2	6.1	0.0	1.3	1.1	21.7
219,500	254 Direct Cycle	5.5	2.5	[illegible]	6.1	0.0	1.3	0.0	19.8
219,500	255 Direct Cycle	5.5	2.5	[illegible]	6.1	0.0	1.3	0.0	23.7

TABLE C6-3 co Weight Breakdown for Na-Cooled Fast Reactor Systems

Shaft Horsepower	Matrix #	δ_{21}	δ_{22}	δ_{23}	δ_{24}	$\delta_{112'}$	$\delta_{11\text{-}4'}$	$\delta_{3'}$	δ_{0}
55,000	346	12.9	5.0	4.5	6.1	0.2	1.3	0.0	30.0
55,000	347	12.95	5.0	2.8	6.1	0.2	1.3	0.0	28.3
55,000	351	12.64	2.5	1.8	6.1	0.1	1.3	0.0	24.4
55,000	352	12.6[illegible]	2.5	2.6	6.1	0.2	1.3	0.0	25.3
55,000	353	12.6[illegible]	2.5	2.9	6.1	0.2	1.3	0.0	25.6
55,000	354	12.64	2.5	3.3	6.1	0.2	1.3	0.0	26.0
55,000	355	12.64	2.5	4.9	6.1	0.2	1.3	0.0	27.6
55,000	366	12.64	5.0	4.5	6.1	0.2	1.3	0.0	30.5
55,000	367	12.64	5.0	2.8	6.1	0.2	1.3	0.0	28.8
110,000	346	7.6	5.0	5.4	6.1	0.0	1.3	0.0	25.4
110,000	347	7.6	5.0	2.8	6.1	0.0	1.3	0.0	22.8
110,000	351	7.31	2.5	1.8	6.1	0.0	1.3	0.0	19.3
110,000	352	7.36	2.5	2.6	6.1	0.0	1.3	0.0	21.1
110,000	353	7.30	2.5	3.4	6.1	0.0	1.3	0.0	22.4
110,000	354	7.30	2.5	3.3	6.1	0.0	1.3	0.0	21.8
110,000	355	7.30	2.5	3.4	6.1	0.0	1.3	0.0	24.4
110,000	366	7.45	5.0	3.4	6.1	0.0	1.3	0.0	26.0
110,000	367	7.45	5.0	2.8	6.1	0.0	1.3	0.0	23.4
164,900	346	5.77	5.0	6.2	6.1	0.0	1.3	0.0	24.4
164,900	347	5.77	5.0	2.8	6.1	0.0	1.3	0.0	21.0
164,900	351	5.44	2.5	1.8	6.1	0.0	1.3	0.0	17.5
164,900	352	5.44	2.5	2.6	6.1	0.0	1.3	0.0	18.3
164,900	353	5.44	2.5	4.[illegible]	6.1	0.0	1.3	0.0	19.9
164,900	354	5.44	2.5	3.3	6.1	0.0	1.3	0.0	19.0
164,900	355	5.44	2.5	6.6	6.1	0.0	1.3	0.0	22.3
164,900	366	5.63	5.0	6.2	6.1	0.0	1.3	0.0	24.2
164,900	367	5.63	5.0	2.8	6.1	0.0	1.3	0.0	20.8
219,800	346	4.77	5.0	6.8	6.1	0.0	1.3	0.0	24.0
219,800	347	4.77	5.0	2.8	6.1	0.0	1.3	0.0	20.0
219,800	351	4.45	2.5	1.8	6.1	0.0	1.3	0.0	16.1
219,800	352	4.45	2.5	2.6	6.1	0.0	1.3	0.0	17.0
219,800	353	4.45	2.5	5.2	6.1	0.0	1.3	0.0	18.2
219,800	354	4.45	2.5	3.3	6.1	0.0	1.3	0.0	17.7
219,800	355	4.45	2.5	7.2	6.1	0.0	1.3	0.0	21.6
219,800	366	4.66	5.0	6.8	6.1	0.0	1.3	0.0	23.9
219,800	367	4.66	5.0	2.8	6.1	0.0	1.3	0.0	19.9

TABLE C6-4 δ_0 Weight Breakdown for Molten Salt Reactor Systems

Shaft Horsepower	Matrix #	δ_{21}	δ_{22}	δ_{23}	δ_{29}	$\delta_{112'}$	$\delta_{114'}$	$\delta_{3'}$	δ_0
11,700	411	25.6	14.1	2.0	6.1	1.1	1.4	1.1	51.4
11,700	412	25.6	14.1	2.8	6.1	1.2	1.4	1.1	52.3
11,700	413	25.6	14.1	1.7	6.1	1.1	1.4	1.1	51.3
11,700	414	25.6	14.1	3.3	6.1	1.2	1.4	1.1	53.0
11,700	415	25.6	14.1	3.6	6.1	1.2	1.4	1.1	53.3
23,400	411	14.9	14.1	1.9	6.1	0.6	1.4	1.1	40.1
23,400	412	14.9	14.1	2.7	6.1	0.6	1.4	1.1	40.9
23,400	413	14.9	14.1	2.1	6.1	0.6	1.4	1.1	40.3
23,400	414	14.9	14.1	3.3	6.1	0.6	1.4	1.1	41.5
23,400	415	14.9	14.1	4.1	6.1	0.7	1.4	1.1	42.3
46,900	411	9.2	14.1	1.8	6.1	0.4	1.3	1.1	34.0
46,900	412	9.2	14.1	2.6	6.1	0.4	1.3	1.1	34.8
46,900	413	9.2	14.1	2.7	6.1	0.4	1.3	1.1	34.9
46,900	414	9.2	14.1	3.3	6.1	0.4	1.3	1.1	35.5
46,900	415	9.2	14.1	4.7	6.1	0.5	1.3	1.1	37.0
93,700	411	6.0	14.1	1.8	6.1	0.3	1.3	1.1	30.7
93,700	412	6.0	14.1	2.6	6.1	0.3	1.3	1.1	31.5
93,700	413	6.0	14.1	3.6	6.1	0.3	1.3	1.1	32.5
93,700	414	6.0	14.1	3.3	6.1	0.3	1.3	1.1	32.2
93,700	415	6.0	14.1	5.6	6.1	0.4	1.3	1.1	34.6
187,400	411	4.1	14.1	1.8	6.1	0.2	1.3	1.1	28.7
187,400	412	4.1	14.1	2.6	6.1	0.3	1.3	1.1	29.6
187,400	413	4.1	14.1	4.8	6.1	0.3	1.3	1.1	31.8
187,400	414	4.1	14.1	3.3	6.1	0.3	1.3	1.1	30.3
187,400	415	4.1	14.1	6.9	6.1	0.4	1.3	1.1	34.0

TABLE C6-5 δ_0 Weight Breakdown for Water-Moderated He-Cooled Reactor Systems

Shaft horsepower	Matrix #	δ_{21}	δ_{22}	δ_{23}	δ_{29}	$\delta_{112'}$	$\delta_{114'}$	$\delta_{3'}$	δ_0
27,300	511	37.7	14.1	1.9	6.1	1.9	1.5	1.1	64.3
27,300	512	37.7	14.1	2.6	6.1	2.0	1.5	1.1	65.1
27,300	513	37.7	14.1	2.2	6.1	1.9	1.5	1.1	64.6
27,300	514	37.7	14.1	3.3	6.1	2.0	1.5	0.0	65.8
27,300	515	37.7	14.1	4.2	6.1	2.1	1.5	0.0	66.8

TABLE C6-6 δ_o Weight Breakdown for Graphite Moderated Gas Cooled Epithermal Reactor Systems

Shaft rsepower	Matrix #	δ_{21}	δ_{22}	δ_{23}	δ_{29}	$\delta_{112'}$	$\delta_{114'}$	$\delta_{3'}$	δ_o
25,000	656 Direct Cycle	34.0		3.7	1.4	0.6	1.4	0.0	41.1
25,000	657 Direct Cycle	34.0		2.8	1.4	0.6	1.4	0.0	40.2
50,000	656 Direct Cycle	19.5		4.4	1.4	0.2	1.3	0.0	26.8
50,000	657 Direct Cycle	19.5		2.8	1.4	0.2	1.3	0.0	25.2
00,000	656 Direct Cycle	14.5		5.3	1.4	0.1	1.3	0.0	22.6
100,000	657 Direct Cycle	14.5		2.8	1.4	0.1	1.3	0.0	20.1
00,000	656 Direct Cycle	9.7		6.6	1.4	0.1	1.3	0.0	19.1
200,000	657 Direct Cycle	9.7		2.8	1.4	0.1	1.3	0.0	15.3
300,000	656 Direct Cycle	8.4		7.6	1.4	0.1	1.3	0.0	18.8
300,000	657 Direct Cycle	8.4		2.8	1.4	0.1	1.3	0.0	14.0
400,000	656 Direct Cycle	7.4		8.4	1.4	0.1	1.3	0.0	18.6
400,000	657 Direct Cycle	7.4		2.8	1.4	0.1	1.3	0.0	13.0

```
C COMPUTERIZED SENSITIVITY ANALYSIS OF CONVENTIONAL DISPLACEMENT VESSELS VARYING
C 1.FULL LOAD DISPLACEMENT(TONS)
C 2.FULL SPEED(KTS)
C 3.RANGE(NM)
C 4.SPECIFIC PROPULSION WEIGHT(LBM/SHP)
C
C
C                    ---CONVENTIONAL DISPLACEMENT VESSEL---
C FULL LOAD DISPLACEMENT (TONS)---1000,2000,3000,4000,5000,6000,7000,8000,9000,
C 10000
C FULL SPEED(KTS)---25,28,30,35,40
C RANGE AT 20 KTS(NM)---1000,2000,4000,6000,8000,10000
C SPECIFIC PROPULSION WEIGHT(LBM/SHP)---5,10,20,30,50,100,120
C
C MANDEL WEIGHT MODEL UTILIZED FOR THIS RUN
C N=NUMBER OF DISPLACEMENT INPUTS, I IS THE MATRIX INDEX
C M=NUMBER OF SPEED INPUTS, J IS THE MATRIX INDEX
C MM= NUMBER OF RANGE INPUTS, K IS THE MATRIX INDEX
C NN=NUMBER OF SPECIFIC PROPULSION WEIGHT INPUTS, L IS THE MATRIX INDEX
C MMM=INDEX OF CRUISE SPEED
C
C
      DIMENSION DISP(10),CV(10),CP(10),BH(10),B(10),D(10),V(10),SHP(10,5
     1),SHPE(10,1),PW(7,10,5),SPW(7),GP1(10),GP3(10,5),GP5(10),PER(10),S
     2TOR(10),STOT(7,10,5),WF(7,10,6,5),RR(6),TOT(7,10,6,5),PAYF(7,10,6,
     35),PAYN(7,10,5),GP6(10)
      REAL LB(10),LL(10)
      DATA KI/5/,KO/6/
C
      READ(KI,1)N,M,MM,NN,MMM
    1 FORMAT(5I2)
      READ(KI,111)(DISP(I),CV(I),CP(I),BH(I),LB(I),I=1,N)
  111 FORMAT(5F10.1)
C
C
      DO 2 I=1,N
```

```
      LL(I)=(DISP(I)*34.997/CV(I))**(1./3.)
      B(I)=LL(I)/LB(I)
      D(I)=B(I)/BH(I)
    2 CONTINUE
C
C
      WRITE(KO,3)
    3 FORMAT('1',28X,'PRINCIPAL DIMENSIONS AND COEFFICIENTS---CONVENTION
     1AL DISPLACEMENT VESSEL')
      WRITE(KO,4) (DISP(I),I=1,N)
    4 FORMAT('-','FULL LOAD DISP(TONS)',5X,6(F10.3,5X))
      WRITE(KO,5) (CP(I),I=1,N)
    5 FORMAT(1X,'PRISMATIC COEFF',10X,6(F10.3,5X))
      WRITE(KO,6) (CV(I),I=1,N)
    6 FORMAT(1X,'VOLUMETRIC COEFF',11X,6(F10.3,5X))
      WRITE(KO,8) (BH(I),I=1,N)
    8 FORMAT(1X,'BEAM/DRAFT RATIO',9X,6(F10.3,5X))
      WRITE(KO,9) (LB(I),I=1,N)
    9 FORMAT(1X,'LENGTH/BEAM RATIO',8X,6(F10.3,5X))
      WRITE(KO,10) (B(I),I=1,N)
   10 FORMAT(1X,'BEAM(FT)',17X,6(F10.3,5X))
      WRITE(KO,11) (LL(I),I=1,N)
   11 FORMAT(1X,'LENGTH (FT)',14X,6(F10.3,5X))
      WRITE(KO,12) (D(I),I=1,N)
   12 FORMAT(1X,'DRAFT (FT)',15X,6(F10.3,5X))
   15 CONTINUE
C
C
C THE FOLLOWING SECTION WILL CALCULATE THE INSTALLED AND ENDURANCE SHP. THEN THE
C REQUIRED FUEL WILL BE CALCULATED
      READ (KI,800) (V(J),J=1,M)
  800 FORMAT(5F10.1)
      READ(KI,999) (RB(K),K=1,MM)
  999 FORMAT(6F10.1)
      DO 350 L=1,NN
      DO 16 I=1,N
```

```
      SLR=V(MMM)/SQRT(LL(I))
      IF(SLR.LT.0.7) GO TO 250
      IF(SLR.LT.1.2) GO TO 251
      IF(SLR.LT.1.5) GO TO 252
      IF(SLR.LT.1.8) GO TO 253
      SHPE(I,MMM)=.0263*V(MMM)**2.45*DISP(I)**.7583
      KE=1
      GO TO 254
  250 SHPE(I,MMM)=.00414*V(MMM)**3*DISP(I)**.6667
      KE=5
      GO TO 254
  251 SHPE(I,MMM)=.002735*V(MMM)**3.33*DISP(I)**.6117
      KE=4
      GO TO 254
  252 SHPE(I,MMM)=.000169*V(MMM)**4.87*DISP(I)**.3550
      KE=3
      GO TO 254
  253 SHPE(I,MMM)=.00677*V(MMM)**3.06*DISP(I)**.6567
      KE=2
  254 CONTINUE
      DO 17 J=1,M
      SLR=V(J)/SQRT(LL(I))
      IF(SLR.LT.0.7) GO TO 150
      IF(SLR.LT.1.2) GO TO 151
      IF(SLR.LT.1.5) GO TO 152
      IF(SLR.LT.1.8) GO TO 153
      SHP(I,J)=0.032*V(J)**2.45*DISP(I)**0.7583
      KS=1
      GO TO 154
  150 SHP(I,J)=0.0513*V(J)**3*DISP(I)**0.6667
      KS=5
      GO TO 154
  151 SHP(I,J)=0.00342*V(J)**3.33*DISP(I)**0.6117
      KS=4
      GO TO 154
  152 SHP(I,J)=0.000222*V(J)**4.87*DISP(I)**0.3550
```

```
      KS=3
      GO TO 154
  153 SHP(I,J)=0.00842*V(J)**3.06*DISP(I)**0.6567
      KS=2
  154 CONTINUE
      XX=SHPE(I,MMM)/SHP(I,J)
      DO 42 K=1,NM
      GO TO (505,505,520,520,550,600,600),L
  505 IF(XX .GT. 0.14) GO TO 506
      SFC=.075/XX**.866
      WF(L,I,K,J)=SHPE(I,MMM)*SFC*RB(K)/2020./V(MMM)
      GO TO 42
  506 SFC=.410/XX**.195
      WF(L,I,K,J)=SHPE(I,MMM)*SFC*RB(K)/2020./V(MMM)
      GO TO 42
  550 SFC=0.34/XX**.0745
      WF(L,I,K,J)=SHPE(I,MMM)*SFC*RB(K)/2020./V(MMM)
      GO TO 42
  600 SFC=0.32/XX**.0786
      WF(L,I,K,J)=SHPE(I,MMM)*SFC*RB(K)/2020./V(MMM)
      GO TO 42
  520 GO TO (311,312,313,304,315),KE
  311 X=.819*(V(MMM)/V(J))**.245
      IF(X .LT. 0.16) GO TO 850
      WF(L,I,K,J)=V(MMM)**1.205*V(J)**.245*DISP(I)**.7583/.132E06*RB(K)
      GO TO 42
  850 WF(L,I,K,J)=V(MMM)**.633*V(J)**.8167*DISP(I)**.7583/.193E06*RB(K)
      GO TO 42
  312 GO TO (881,882),KS
  881 X=.211*V(MMM)**3.06/DISP(I)**.1017/V(J)**2.45
      IF(X .LT. 0.16) GO TO 851
      WF(L,I,K,J)=V(MMM)**1.754*V(J)**.245*DISP(I)**.6668/.448E06*RB(K)
      GO TO 42
  851 WF(L,I,K,J)=V(MMM)**1.04*V(J)**.8167*DISP(I)**.6906/.477E06*RB(K)
      GO TO 42
  882 X=.804*(V(MMM)/V(J))**3.06
```

```
      IF(X .LT. 0.16) GO TO 852
      WF(L,I,K,J)=V(MMM)**1.754*V(J)**.306*DISP(I)**.6567/.513E06*RB(K)
      GO TO 42
  852 WF(L,I,K,J)=V(MMM)**1.04*V(J)**1.02*DISP(I)**.6567/.745E06*RB(K)
      GO TO 42
  313 GO TO (891,892,893),KS
  891 X=.00526*V(MMM)**4.87/DISP(I)**.4033/V(J)**2.45
      IF(X .LT. 0.16) GO TO 853
      WF(L,I,K,J)=V(MMM)**3.383*V(J)**.245*DISP(I)**.3953/12.38E06*RB(K)
      GO TO 42
  853 WF(L,I,K,J)=V(MMM)**2.247*V(J)**.8167*DISP(I)**.4893/5.58E06*RB(K)
      GO TO 42
  892 X=.0201*V(MMM)**4.87/DISP(I)**.3017/V(J)**3.06
      IF(X .LT. 0.16) GO TO 854
      WF(L,I,K,J)=V(MMM)**3.383*V(J)**.306*DISP(I)**.3852/14.2E06*RB(K)
      GO TO 42
  854 WF(L,I,K,J)=V(MMM)**2.247*V(J)**1.02*DISP(I)**.4556/8.72E06*RB(K)
      GO TO 42
  893 X=.761*(V(MMM)/V(J))**4.87
      IF(X .LT. 0.16) GO TO 855
      WF(L,I,K,J)=V(MMM)**3.383*V(J)**.487*DISP(I)**.355/20.4E06*RB(K)
      GO TO 42
  855 WF(L,I,K,J)=V(MMM)**2.247*V(J)**1.623*DISP(I)**.355/29.35E06*RB(K)
      GO TO 42
  304 GO TO (401,402,403,404),KS
  401 X=.0851*V(MMM)**3.33/V(J)**2.45/DISP(I)**.1466
      IF(X .LT. 0.16) GO TO 83
      WF(L,I,K,J)=V(MMM)**2*V(J)**.245*DISP(I)**.6263/1.013E06*RB(K)
      GO TO 42
   83 WF(L,I,K,J)=V(MMM)**1.22*V(J)**.8167*DISP(I)**.6606/.873E06*RB(K)
      GO TO 42
  402 X=.325*V(MMM)**3.33/V(J)**3.06/DISP(I)**.045
      IF(X .LT. 0.16) GO TO 84
      WF(L,I,K,J)=V(MMM)**2*V(J)**.306*DISP(I)**.6162/1.159E06*RB(K)
      GO TO 42
   84 WF(L,I,K,J)=V(MMM)**1.22*V(J)**1.02*DISP(I)**.6267/1.365E06*RB(K)
```

```
      GO TO 42
  403 X=DISP(I)**.2567*V(MMM)**3.33/.0811/V(J)**4.87
      IF(X .LT. 0.16) GO TO 85
      WF(L,I,K,J)=V(MMM)**2*V(J)**.487*DISP(I)**.5860/1.667E06*RB(K)
      GO TO 42
   85 WF(L,I,K,J)=V(MMM)**1.22*V(J)**1.623*DISP(I)**.5261/4.590E06*RB(K)
      GO TO 42
  404 X=.799*(V(MMM)/V(J))**3.33
      IF(X .LT. 0.16) GO TO 86
      WF(L,I,K,J)=V(MMM)**2*V(J)**.333*DISP(I)**.6117/1.22E06*RB(K)
      GO TO 42
   86 WF(L,I,K,J)=V(MMM)**1.22*V(J)**1.111*DISP(I)**.6117/1.844E06*RB(K)
      GO TO 42
  315 GO TO (981,982,983,984,985),KS
  981 X=.129*V(MMM)**3/V(J)**2.45/DISP(I)**.0913
      IF(X .LT. 0.16) GO TO 856
      WF(L,I,K,J)=V(MMM)**1.7*V(J)**.245*DISP(I)**.6758/.697E06*RB(K)
      GO TO 42
  856 WF(L,I,K,J)=V(MMM)*V(J)**.8167*DISP(I)**.6972/.663E06*RB(K)
      GO TO 42
  982 X=V(MMM)**3*DISP(I)**.01/2.03/V(J)**3.06
      IF(X .LT. 0.16) GO TO 857
      WF(L,I,K,J)=V(MMM)**1.7*V(J)**.306*DISP(I)**.6657/.798E06*RB(K)
      GO TO 42
  857 WF(L,I,K,J)=V(MMM)*V(J)**1.02*DISP(I)**.6633/1.037E06*RB(K)
      GO TO 42
  983 X=V(MMM)**3*DISP(I)**.312/.0535/V(J)**4.87
      IF(X .LT. 0.16) GO TO 858
      WF(L,I,K,J)=V(MMM)**1.7*V(J)**.487*DISP(I)**.6355/1.148E06*RB(K)
      GO TO 42
  858 WF(L,I,K,J)=V(MMM)*V(J)**1.623*DISP(I)**.5627/3.485E06*RB(K)
      GO TO 42
  984 X=V(MMM)**3*DISP(I)**.055/.825/V(J)**3.33
      IF(X .LT. 0.16) GO TO 859
      WF(L,I,K,J)=V(MMM)**1.7*V(J)**.333*DISP(I)**.6612/.873E06*RB(K)
      GO TO 42
```

```
859 WF(L,I,K,J)=V(MMM)*V(J)**1.11*DISP(I)**.6483/1.398E06*RB(K)
985 X=.807*(V(MMM)/V(J))**3
    IF(X .LT. 0.16) GO TO 860
    WF(L,I,K,J)=V(MMM)**1.7*V(J)**.3*DISP(I)**.6667/.838E06*RB(K)
    GO TO 42
860 WF(L,I,K,J)=V(MMM)*V(J)*DISP(I)**.6667/1.222E06*RB(K)
    GO TO 42
 42 CONTINUE
 17 CONTINUE
 16 CONTINUE
350 CONTINUE
C
    WRITE(KO,30)
 30 FORMAT('1','FULL LOAD DISPL',10X,'MAXIMUM SPEED',10X,'INSTALLED SH
   1P',10X,'ENDURANCE SHP')
    WRITE(KO,31)((DISP(I),V(J),SHP(I,J),SHPE(I,MMM),J=1,M),I=1,N)
 31 FORMAT(4X,F7.1,19X,F4.1,16X,F8.1,15X,F8.1)
C
C DIFFERENT GROUP 1'+2+3' SPECIFIC PROPULSION WEIGHTS WILL BE UTILIZED TO
C CALCULATE HPDV PROPULSION WEIGHTS
C
    READ(KI,801) (SPW(L),L=1,NN)
801 FORMAT(7F10.1)
    DO 32 L=1,NN
    DO 33 I=1,N
    DO 34 J=1,M
    PW(L,I,J)=SHP(I,J)*SPW(L)/2240.
 34 CONTINUE
 33 CONTINUE
 32 CONTINUE
    DO 35 L=1,NN
    WRITE(KO,36) SPW(L)
 36 FORMAT('1',26X,'PROPULSION WEIGHTS---CONVENTIONAL DISPLACEMENT VES
   1SEL    (',F6.1,'LBM/SHP)')
    WRITE(KO,37)
 37 FORMAT('- FULL LOAD DISPL',10X,'SPEED',20X,'SHP',10X,'PROPULSION W
```

```
     1EIGHT')
      WRITE(KO,38)  ((DISP(I),V(J),SHP(I,J),PW(L,I,J),J=1,M),I=1,N)
   38 FORMAT(4X,F8.1,15X,F4.1,18X,F8.1,10X,F8.1)
   35 CONTINUE
C
C
      DO 40 I=1,N
      DO 41 J=1,M
      GP1(I)=0.30*DISP(I)
      GP3(I,J)=0.33*DISP(I)**(2./3.)+.001*SHP(I,J)
      GP5(I)=0.583*(.065*DISP(I)+1.25*DISP(I)**(2./3.))
      GP6(I)=0.417*(.065*DISP(I)+1.25*DISP(I)**(2./3.))
      PER(I)=.03022*DISP(I)
      STOR(I)=.00378*DISP(I)
   41 CONTINUE
   40 CONTINUE
      DO 501 L=1,NN
      DO 502 I=1,N
      DO 503 J=1,M
      STOT(L,I,J)=GP1(I)+GP3(I,J)+GP5(I)+GP6(I)+PER(I)+STOR(I)+PW(L,I,J)
  503 CONTINUE
  502 CONTINUE
  501 CONTINUE
      DO 43 L=1,NN
      DO 44 I=1,N
      DO 45 K=1,MM
      DO 46 J=1,M
      TOT(L,I,K,J)=STOT(L,I,J)+WF(L,I,K,J)
      PAYF(L,I,K,J)=DISP(I)-TOT(L,I,K,J)
      PAYN(L,I,J)=DISP(I)-STOT(L,I,J)
   46 CONTINUE
   45 CONTINUE
   44 CONTINUE
   43 CONTINUE
      DO 47 L=1,NN
      DO 48 I=1,N
```

```
      WRITE(KC,450) SPW(L)
  450 FORMAT('1',25X,'FUEL WEIGHT AND PAYLOAD FOR CONVENTIONAL DISPLACEM
     1ENT VESSEL     (',F6.1,'LBM/SHP)')
      WRITE(KO,60) DISP(I),(V(J),J=1,M)
   60 FORMAT('-FULL LOAD DISPL=',F7.0,5(12X,F4.1,'KTS'))
      WRITE(KO,61)  GP1(I),GP1(I),GP1(I),GP1(I),GP1(I)
   61 FORMAT(1X,'GP1',28X,5(F9.0,10X))
      WRITE(KO,62) (PW(L,I,J),J=1,M)
   62 FORMAT(1X,'GP2',28X,5(F9.0,10X))
      WRITE(KO,63) (GP3(I,J),J=1,M)
   63 FORMAT(1X,'GP3',28X,5(F9.0,10X))
      WRITE(KO,64)  GP5(I),GP5(I),GP5(I),GP5(I),GP5(I)
   64 FORMAT(1X,'GP5',28X,5(F9.0,10X))
      WRITE(KO,65)  GP6(I),GP6(I),GP6(I),GP6(I),GP6(I)
   65 FORMAT(1X,'GP6',28X,5(F9.0,10X))
      WRITE(KO,66) PER(I),PER(I),PER(I),PER(I),PER(I)
   66 FORMAT(1X,'PERSONNEL',22X,5(F9.0,10X))
      WRITE(KO,67)  STOR(I),STOR(I),STOR(I),STOR(I),STOR(I)
   67 FORMAT(1X,'STORES',25X,5(F9.0,10X))
      WRITE(KO,68) (STOT(L,I,J),J=1,M)
   68 FORMAT(1X,'SUB-TOTAL',22X,5(F9.0,10X))
      DO 300 K=1,MM
      WRITE(KO,69) RB(K),(WF(L,I,K,J),J=1,M)
   69 FORMAT(1X,'FUEL WT.',1X,F7.0,'NM',14X,5(F9.0,10X))
      WRITE(KO,70)  RB(K),(TOT(L,I,K,J),J=1,M)
   70 FORMAT(1X,'TOTAL',F7.0,20X,5(F9.0,10X))
  300 CONTINUE
      DO 301 K=1,MM
      WRITE(KO,71) DISP(I),DISP(I),DISP(I),DISP(I),DISP(I)
   71 FORMAT(1X,'FULL LOAD DISPL',16X,5(F9.0,10X))
      WRITE(KO,73)  RB(K),(PAYF(L,I,K,J),J=1,M)
   73 FORMAT(1X,'PAYLOAD',1X,F8.1,'NM',14X,5(F9.0,10X))
  301 CONTINUE
      WRITE(KO,74) (PAYN(L,I,J),J=1,M)
   74 FORMAT(1X,'PAYLOAD NUCLEAR PLANT',10X,5(F9.0,10X))
   48 CONTINUE
```

```
   47 CONTINUE
  998 CONTINUE
      STOP
      END
```

```
C COMPUTERIZED SENSITIVITY ANALYSIS OF HIGH PERFORMANCE NAVAL VESSELS VARYING:
C 1.FULL LOAD DISPLACEMENT(TONS)
C 2.FULL SPEED(KTS)
C 3.RANGE(NM)
C 4.SPECIFIC PROPULSION WEIGHT(LBM/SHP)
C
C
C                                  ----HPDV----
C SERIES 64 MODEL 4803 UTILIZED FOR THIS RUN, HOC CRITERIA
C FULL LOAD DISPLACEMENT(TONS)---1000,2000,3000,4000
C FULL SPEED(KTS)---20,30,40,50,60
C RANGE AT 20 KTS(NM)---1000,2000,3000,4000,5000,6000
C SPECIFIC PROPULSION WEIGHT(LBM/SHP)---5,10,20,30,50,100,120
C
C N=NUMBER OF DISPLACEMENT INPUTS, I IS THE MATRIX INDEX
C M=NUMBER OF SPEED INPUTS, J IS THE MATRIX INDEX
C MM= NUMBER OF RANGE INPUTS, K IS THE MATRIX INDEX
C NN=NUMBER OF SPECIFIC PROPULSION WEIGHT INPUTS, L IS THE MATRIX INDEX
C MMM=INDEX OF CRUISE SPEED
C IF KT=2 THE PROGRAM STOPS
C
C
      DIMENSION DISP(4),CB(4),BH(4),DLR(4),SDL(4),RRDR(26),SLRR(26),B(4
     1),D(4),S(4),CX(4),VFPS(5),V(5),EHP(4,5),SHP(4,5),PC(5),PW(7,4,5),S
     2PW(7),GP1(4),GP3(4),GP5(4),PER(4),STOR(4),STOT(7,4,5),WF(7,4,3,6),
     3RB(7),TCT(7,4,6,5),PAYF(7,4,6,5),PAYN(7,4,5),GP6(4)
      REAL LB(4),LL(4),NU
      DATA KI/5/,KO/6/,RHO/1.9905/,NU/1.2791E-05/,DCP/0.0004/
C
      READ(KI,1)N,M,MM,NN,MMM
    1 FORMAT(5I1)
      READ(KI,111)(DISP(I),CB(I),CX(I),BH(I),DLR(I),LB(I),SDL(I),I=1,N)
  111 FORMAT(7F10.1)
      READ(KI,24)(SLRR(II),RRDR(II),II=1,26)
   24 FORMAT(7F10.2)
      READ(KI,901)(SPW(L),L=1,NN)
```

```
801 FORMAT(7F10.1)
    READ(KI,302)GPF1,GPF3,GPF5,GPF6,PERF,STORF
302 FORMAT(6F10.3)
    READ(KI,999) (RB(K),K=1,MM)
999 FORMAT(6F10.1)
850 READ(KI,333) KT
333 FORMAT(I1)
    IF(KT .EQ. 2)GO TO 998
    READ(KI,800) (V(J),PC(J),J=1,M)
800 FORMAT(3F10.1)
C
C
    DO 2 I=1,N
    LL(I)=(DISP(I)*34.997*BH(I)*LB(I)**2/CB(I))**(1./3.)
    B(I)=LL(I)/LB(I)
    D(I)=B(I)/BH(I)
    S(I)=(SQRT(DISP(I)*LL(I)))*SDL(I)
  2 CONTINUE
C
C
    WRITE(KO,3)
  3 FORMAT('1',42X,'PRINCIPAL DIMENSIONS AND COEFFICIENTS---HPDV'/' ',
   152X,'MODEL NO.4803 SERIES 64')
    WRITE(KO,4) (DISP(I),I=1,N)
  4 FORMAT('-','FULL LOAD DISP(TONS)',5X,4(F10.3,10X))
    WRITE(KO,5) (CB(I),I=1,N)
  5 FORMAT(1X,'BLOCK COEFF',14X,4(F10.3,10X))
    WRITE(KO,6) (CX(I),I=1,N)
  6 FORMAT(1X,'MAX SECT AREA COEFF',6X,4(F10.3,10X))
    WRITE(KO,7) (DLR(I),I=1,N)
  7 FORMAT(1X,'DISPL/LENGTH RATIO',7X,4(F10.3,10X))
    WRITE(KO,8) (BH(I),I=1,N)
  8 FORMAT(1X,'BEAM/DRAFT RATIO',9X,4(F10.3,10X))
    WRITE(KO,9) (LB(I),I=1,N)
  9 FORMAT(1X,'LENGTH/BEAM RATIO',8X,4(F10.3,10X))
    WRITE(KO,10) (B(I),I=1,N)
```

```
   10 FORMAT(1X,'BEAM(FT)',17X,4(F10.3,10X))
      WRITE(KO,11) (LL(I),I=1,N)
   11 FORMAT(1X,'LENGTH (FT)',14X,4(F10.3,10X))
      WRITE(KO,12) (D(I),I=1,N)
   12 FORMAT(1X,'DRAFT (FT)',15X,4(F10.3,10X))
      WRITE(KO,13) (SDL(I),I=1,N)
   13 FORMAT(1X,'S/(SQRT(DISPL*LENGTH))',3X,4(F10.3,10X))
      WRITE(KO,14) (S(I),I=1,N)
   14 FORMAT(1X,'S(FT**2)',17X,4(F10.3,10X))
   15 CONTINUE
C
C
C THE NEXT SECTION WILL CALCULATE THE REQUIRED EHP AND SHP FOR THE VARIOUS
C DISPLACEMENTS FOR EACH OF THE SPEEDS. SERIES 64 DATA WILL BE UTILIZED ALONG
C WITH THE ITTC LINE
C
C
      DO 16 I=1,N
      DO 17 J=1,M
      VFPS(J)=V(J)*1.689
      RE=VFPS(J)*LL(I)/NU
      CF=(0.075)/(ALOG10(RE)-2.)**2
C
C THE FOLLOWING SECTION WILL INTERPOLATE FOR A GIVEN SPEED-LENGTH RATIO,
C DISPLACEMENT-LENGTH RATIO, BEAM-DRAFT RATIO, THE RESIDUARY RESISTANCE IN
C POUNDS PER TON OF DISPLACEMENT FOR A GIVEN BLOCK COEFFICIENT
C
      SLR=V(J)/SQRT(LL(I))
      DO 25 II=1,27
      IF(SLR-SLRR(II)) 100,101,25
  100 RRD=((SLR-SLRR(II-1))/(SLRR(II)-SLRR(II-1))*(RRDR(II)-RRDR(II-1)))
     1+RRDR(II-1)
      GO TO 990
  101 RRD=RRDR(II)
      GO TO 990
   25 CONTINUE
```

```
  990 RR=RRD*DISP(I)
      RTBH=0.5*RHO*S(I)*VFPS(J)**2*(CF+DCF)+RR
      RT=1.1*RTBH
      EHP(I,J)=1.2375*RT*VFPS(J)/550.
C
C NOW, DEPENDING ON THE SPEED, A PROPULSIVE COEFFICIENT FOR SUPERCAVITATING
C PROPELLERS WILL BE USED TO FIND REQUIRED SHAFT HORSEPOWER
C
      SHP(I,J)=EHP(I,J)/PC(J)
   17 CONTINUE
   16 CONTINUE
C
      WRITE(KO,30)
   30 FORMAT('1','FULL LOAD DISPL',10X,'SPEED',10X,'EHP',10X,'PROP. COEF
     1F.',10X,'SHP')
      WRITE(KO,31) ((DISP(I),V(J),EHP(I,J),PC(J),SHP(I,J),J=1,M),I=1,N)
   31 FORMAT(4X,F6.1,17X,F4.1,8X,F8.1,12X,F4.2,12X,F8.1)
C
C DIFFERENT GROUP 1'+2+3' SPECIFIC PROPULSION WEIGHTS WILL BE UTILIZED TO
C CALCULATE HPDV PROPULSION WEIGHTS
C
      DO 32 L=1,NN
      DO 33 I=1,N
      DO 34 J=1,M
      PW(L,I,J)=SHP(I,J)*SPW(L)/2240.
   34 CONTINUE
   33 CONTINUE
   32 CONTINUE
      DO 35 L=1,NN
      WRITE(KO,36) SPW(L)
   36 FORMAT('1',44X,'PROPULSION WEIGHTS---HPDV     (',F6.1,' LBM/SHP)')
      WRITE(KO,37)
   37 FORMAT('- FULL LOAD DISPL',10X,'SPEED',20X,'SHP',10X,'PROPULSION W
     1EIGHT')
      WRITE(KO,38) ((DISP(I),V(J),SHP(I,J),PW(L,I,J),J=1,M),I=1,N)
   38 FORMAT(4X,F6.1,17X,F4.1,18X,F8.1,10X,F8.1)
```

```
   35 CONTINUE
C
C NEXT FOR VARIOUS FULL LOAD DISPLACEMENTS, VARIOUS SPEEDS, AND VARIOUS SPECIFIC
C PROPULSION WEIGHT, FUEL WEIGHT REQUIRED FOR A CRUISE SPEED OF 20 KNOTS
C IS CALCULATED.  THEN KNOWING GROUP WEIGHT FRACTIONS, THE PAYLOAD CAN BE
C DETERMINED.
C
      DO 40 I=1,N
      GP1(I)=GPF1*DISP(I)
      GP3(I)=GPF3*DISP(I)
      GP5(I)=GPF5*DISP(I)
      GP6(I)=GPF6*DISP(I)
      PER(I)=PERF*DISP(I)
      STOP(I)=STORF*DISP(I)
   40 CONTINUE
      DO 401 L=1,NN
      DO 402 I=1,N
      DO 403 J=1,M
      STOT(L,I,J)=GP1(I)+GP3(I)+GP5(I)+GP6(I)+PER(I)+STOR(I)+PW(L,I,J)
  403 CONTINUE
  402 CONTINUE
  401 CONTINUE
      DO 900 L=1,NN
      DO 41 I=1,N
      DO 42 K=1,MM
      DO 901 J=1,M
      X=SHP(I,MMM)/SHP(I,J)
      GO TO (505,505,520,520,550,600,600),I
  505 IF(X .GT. 0.14) GO TO 506
      SFC=.075/X**.866
      GO TO 802
  506 SFC=.410/X**.185
      GO TO 802
  520 IF(X .GT. 0.16) GO TO 507
      SFC=.57/X**.1
      GO TO 802
```

```
507 SFC=.372/Y**(1./3.)
    GO TO 802
550 SFC=0.34/Y**.0745
    GO TO 802
600 SFC=0.32/X**.0786
    GO TO 802
802 CONTINUE
    Y=EXP(RB(K)*SFC*SHP(I,1)/(2240.*DISP(I)*V(1)))
    WF(L,I,K,J)=1.108*DISP(I)*(Y-1.)/Y
901 CONTINUE
 42 CONTINUE
 41 CONTINUE
900 CONTINUE
    DO 43 L=1,NN
    DO 44 I=1,N
    DO 45 K=1,MM
    DO 46 J=1,M
    TOT(L,I,K,J)=STOT(L,I,J)+WF(L,I,K,J)
    PAYF(L,I,K,J)=DISP(I)-TOT(L,I,K,J)
    PAYN(L,I,J)=DISP(I)-STOT(L,I,J)
 46 CONTINUE
 45 CONTINUE
 44 CONTINUE
 43 CONTINUE
    DO 47 L=1,NN
    DO 48 I=1,N
    WRITE(KO,450)SPW(L)
450 FORMAT('1  ',40X,'FUEL WEIGHT AND PAYLOAD FOR HPDV  (',F6.1,' LBM/
   1SHP)')
    WRITE(KO,60)DISP(I),(V(J),J=1,M)
 60 FORMAT('- FULL LOAD DISPL=',F6.1,5(12X,F4.1,'KTS'))
    WRITE(KO,61) GP1(I),GP1(I),GP1(I),GP1(I),GP1(I)
 61 FORMAT(1X,'GP1',28X,5(F9.0,10X))
    WRITE(KO,62) (PW(L,I,J),J=1,M)
 62 FORMAT(1X,'GP2',28X,5(F9.0,10X))
    WRITE(KO,63) GP3(I),GP3(I),GP3(I),GP3(I),GP3(I)
```

```
 63 FORMAT(1X,'GP3',28X,5(F9.0,10X))
    WRITE(KO,64) GP5(I),GP5(I),GP5(I),GP5(I),GP5(I)
 64 FORMAT(1X,'GP5',28X,5(F9.0,10X))
    WRITE(KO,65) GP6(I),GP6(I),GP6(I),GP6(I),GP6(I)
 65 FORMAT(1X,'GP6',28X,5(F9.0,10X))
    WRITE(KO,66) PER(I),PER(I),PER(I),PER(I),PER(I)
 66 FORMAT(1X,'PERSONNEL',22X,5(F9.0,10X))
    WRITE(KO,67) STOR(I),STOR(I),STOR(I),STOR(I),STOR(I)
 67 FORMAT(1X,'STORES',25X,5(F9.0,10X))
    WRITE(KO,68) (STOT(L,I,J),J=1,M)
 68 FORMAT(1X,'SUB-TOTAL',22X,5(F9.0,10X))
    DO 300 K=1,MM
    WRITE(KO,69) RB(K),(WF(L,I,K,J),J=1,M)
 69 FORMAT(1X,'FUEL WT.',1X,F6.1,'NM',14X,5(F9.0,10X))
    WRITE(KO,70) RB(K),(TOT(L,I,K,J),J=1,M)
 70 FORMAT(1X,'TOTAL',F6.1,20X,5(F9.0,10X))
300 CONTINUE
    DO 301 K=1,MM
    WRITE(KO,71) DISP(I),DISP(I),DISP(I),DISP(I),DISP(I)
 71 FORMAT(1X,'FULL LOAD DISPL',16X,5(F9.0,10X))
    WRITE(KO,73) RB(K),(PAYF(L,I,K,J),J=1,M)
 73 FORMAT(1X,'PAYLOAD',1X,F7.2,'NM',14X,5(F9.0,10X))
301 CONTINUE
    WRITE(KO,74) (PAYN(L,I,J),J=1,M)
 74 FORMAT(1X,'PAYLOAD NUCLEAR PLANT',10X,5(F9.0,10X))
 48 CONTINUE
 47 CONTINUE
112 GO TO 850
998 CONTINUE
    STOP
    END
```

```
C CCMPUTERIZED SENSITIVITY ANALYSIS CF HYCRCFCILS VARYING:
C 1.FULL LCAC CISPLACEMENT(TCNS)
C 2.FULL SPEED(KTS)
C 3.RANGE(NM)
C 4.SPECIFIC PRCPULSICN WEIGHT(LBM/SHP)
C
C
C                          ---HYCRCFOIL---
C FULL LOAD CISPLACEMENT(TCNS)---230,750,1278
C FULL SPEED---2C,25,30,35,4C,45,50
C RANGE AT 20 KTS(NM)---1CCC,2CCC,3C00,40CC,5CCC,6000
C SPECIFIC PROPULSION WEIGHT(LBM/SHP)---5,10,20,30,50,100,120
C
C PHM AND HCC CRAG CURVES UTILIZED FCR HYCRCFCIL MODEL
C N=NUMBER OF DISPLACEMENT INPUTS, I IS THE MATRIX INDEX
C M=NUMBER CF SPEEC INPUTS, J IS THE MATRIX INCEX
C MM= NUMBER OF RANGE INPUTS, K IS THE MATRIX INDEX
C NN=NUMBER CF SPECIFIC PRCPULSICN WEIGHT INPUTS, L IS THE MATRIX INDEX
C MMM=INDEX CF CRUISE SPEEC
C
      DIMENSION CISP(5),CB(5),BH(5),SDL(5),B(5),D(5),S(5),CX(5),V(7),
     1SHP(5,7),PC(7),DW(5,7),PW(7,5,7),SPW(7),GP1(5),GPF1(5),GP3(5),GP
     2F3(5),GP5(5),GPF5(5),GP6(5),GPF6(5),PER(5),PERF(5),FOIL(5),FCIL
     3F(5),STOT(7,5,7),WF(7,7,7,7),RB(6),TCT(7,7,7,7),PAYF(7,7,7,7),PAYN
     4(7,7,7)
      REAL LB(5),LL(5)
      DATA KI/5/,KC/6/
      READ(KI,1)N,M,MM,NN,MMM
    1 FORMAT(5I1)
      READ(KI,111)(CISP(I),CB(I),BH(I),LB(I),CX(I),SDL(I),I=1,N)
  111 FORMAT(6F10.1)
      READ(KI,801)((DW(I,J),J=1,M),I=1,N)
  801 FORMAT(7F1C.5)
      READ(KI,990)(GPF1(I),GPF3(I),GPF5(I),GPF6(I),PERF(I),FCILF(I),I=1,
     1N)
  990 FORMAT(6F1C.3)
```

```
      READ(KI,811) (SPW(L),L=1,NN)
  811 FORMAT(7F10.1)
      READ(KI,999) (RB(K),K=1,MM)
  999 FORMAT(5F10.1)
  850 READ(KI,333) KE
  333 FORMAT(I1)
      IF(KE .EQ. 2) GO TO 998
      READ(KI,800) (V(J),PC(J),J=1,M)
  800 FORMAT(8F10.1)
C
C
      DO 2 I=1,N
      LL(I)=(DISP(I)*34.997*BH(I)*LB(I)**2/CB(I))**(1./3.)
      B(I)=LL(I)/LB(I)
      D(I)=B(I)/BH(I)
      S(I)=(SQRT(DISP(I)*LL(I)))*SDL(I)
    2 CONTINUE
C
C
      WRITE(KO,3)
    3 FORMAT('1',42X,'PRINCIPAL DIMENSIONS AND COEFFICIENTS---HYDROFOIL'
     1)
      WRITE(KO,4) (DISP(I),I=1,N)
    4 FORMAT('-','FULL LOAD DISP(TONS)',5X,4(F10.3,10X))
      WRITE(KO,5) (CB(I),I=1,N)
    5 FORMAT(1X,'BLOCK COEFF',14X,4(F10.3,10X))
      WRITE(KO,6) (CX(I),I=1,N)
    6 FORMAT(1X,'MAX SECT AREA COEFF',6X,4(F10.3,10X))
      WRITE(KO,8) (BH(I),I=1,N)
    8 FORMAT(1X,'BEAM/DRAFT RATIO',9X,4(F10.3,10X))
      WRITE(KO,9) (LB(I),I=1,N)
    9 FORMAT(1X,'LENGTH/BEAM RATIO',8X,4(F10.3,10X))
      WRITE(KO,10) (B(I),I=1,N)
   10 FORMAT(1X,'BEAM(FT)',17X,4(F10.3,10X))
      WRITE(KO,11) (LL(I),I=1,N)
   11 FORMAT(1X,'LENGTH (FT)',14X,4(F10.3,10X))
```

```
      WRITE(KO,12) (D(I),I=1,N)
   12 FORMAT(1X,'DRAFT (FT)',15X,4(F10.3,10X))
      WRITE(KO,13) (SDL(I),I=1,N)
   13 FORMAT(1X,'S/(SQRT(DISPL*LENGTH))',3X,4(F10.3,10X))
      WRITE(KC,14) (S(I),I=1,M)
   14 FORMAT(1X,'S(FT**2)',17X,4(F10.3,10X))
   15 CONTINUE
C
C
C THE NEXT SECTION WILL CALCULATE THE REQUIRED SHP FOR A GIVEN DRAG/WEIGHT
C RATIO FOR A GIVEN SPEED AND PROPULSIVE COEFFICIENT DEPENDING ON WHETHER
C THE PROPULSOR IS A WATERJET,SUBCAVITATING, OR SUPERCAVITATING PROPELLER
C
C
      DO 16 I=1,N
      DO 17 J=1,M
      SHP(I,J)=6.88*DW(I,J)/PC(J)*V(J)*DISP(I)
   17 CONTINUE
   16 CONTINUE
C
      WRITE(KO,30)
   30 FORMAT('1','FULL LOAD DISPL',10X,'SPEED',12X,'D/W',12X,'PROP. COEF
     1F.',10X,'SHP')
      WRITE(KO,31) ((DISP(I),V(J),DW(I,J),PC(J),SHP(I,J),J=1,M),I=1,N)
   31 FORMAT(4X,F6.1,17X,F4.1,8X,F7.5,13X,F4.2,11X,F10.1)
C
C DIFFERENT GROUP 1'+2+3' SPECIFIC PROPULSION WEIGHTS WILL BE UTILIZED TO
C CALCULATE HYDROFOIL PROPULSION WEIGHTS
C
      DO 32 L=1,NN
      DO 33 I=1,N
      DO 34 J=1,M
      PW(L,I,J)=SHP(I,J)*SPW(L)/2240.
   34 CONTINUE
   33 CONTINUE
   32 CONTINUE
```

```
      DO 35 L=1,NN
      WRITE(KO,36) SPW(L)
   36 FORMAT('1',44X,'PROPULSION WEIGHTS---HYDROFOIL  (',F6.1,' LBM/SHP)
     1')
      WRITE(KO,37)
   37 FORMAT('- FULL LOAD DISPL',10X,'SPEED',20X,'SHP',10X,'PROPULSION W
     1EIGHT')
      WRITE(KO,38) ((DISP(I),V(J),SHP(I,J),PW(L,I,J),J=1,M),I=1,N)
   38 FORMAT(4X,F6.1,17X,F4.1,18X,F8.1,10X,F8.1)
   35 CONTINUE
C
C NEXT FOR VARIOUS FULL LOAD DISPLACEMENTS, VARIOUS SPEEDS, AND VARIOUS SPECIFIC
C PROPULSION WEIGHT, FUEL WEIGHT REQUIRED FOR A CRUISE SPEED OF 20 KNOTS
C IS CALCULATED.  THEN KNOWING GROUP WEIGHT FRACTIONS, THE PAYLOAD CAN BE
C DETERMINED.
C
      DO 40 I=1,N
      GP1(I)=GPF1(I)*DISP(I)
      GP3(I)=GPF3(I)*DISP(I)
      GP5(I)=GPF5(I)*DISP(I)
      GP6(I)=GPF6(I)*DISP(I)
      PER(I)=PERF(I)*DISP(I)
      FOIL(I)=FOILF(I)*DISP(I)
   40 CONTINUE
      DO 401 L=1,NN
      DO 402 I=1,N
      DO 403 J=1,M
      STOT(L,I,J)=GP1(I)+GP3(I)+GP5(I)+GP6(I)+PER(I)+FOIL(I)+PW(L,I,J)
  403 CONTINUE
  402 CONTINUE
  401 CONTINUE
      DO 400 L=1,NN
      DO 41 I=1,N
      DO 42 K=1,MM
      DO 555 J=1,M
      X=SHP(I,MMM)/SHP(I,J)
```

```
      GO TO (505,505,520,520,550,600,600),L
  505 IF(X .GT. 0.14) GO TO 506
      SFC=.075/X**.866
      GO TO 802
  506 SFC=.410/X**.135
      GO TO 802
  520 IF(X .GT. 0.16) GO TO 507
      SFC=.57/X**.1
      GO TO 802
  507 SFC=.372/X**(1./3.)
      GO TO 802
  550 SFC=0.34/X**.0745
      GO TO 802
  600 SFC=0.32/X**.0786
      GO TO 802
  802 CONTINUE
      Y=EXP(RP(K)*SFC*SHP(I,MMM)/(2240.*DISP(I)*V(MMM)))
      WF(L,I,K,J)=1.108*DISP(I)*(Y-1.)/Y
  555 CONTINUE
   42 CONTINUE
   41 CONTINUE
  400 CONTINUE
      DO 43 L=1,NN
      DO 44 I=1,N
      DO 45 K=1,MM
      DO 46 J=1,M
      TOT(L,I,K,J)=STOT(L,I,J)+WF(L,I,K,J)
      PAYF(L,I,K,J)=DISP(I)-TOT(L,I,K,J)
      PAYN(L,I,J)=DISP(I)-STOT(L,I,J)
   46 CONTINUE
   45 CONTINUE
   44 CONTINUE
   43 CONTINUE
      DO 47 L=1,NN
      DO 48 I=1,N
      WRITE(KO,450)SPW(L)
```

```
450 FORMAT('1',40X,'FUEL WEIGHT AND PAYLOAD FOR HYDROFOIL(',F6.1,'LBM/
   1SHP)')
    WRITE(KO,60)DISP(I),(V(J),J=1,M)
 60 FORMAT('- FULL LOAD DISPL=',F6.1,5X,7(F4.1,'KTS',5X))
    WRITE(KO,61) GP1(I),GP1(I),GP1(I),GP1(I),GP1(I),GP1(I),GP1(I)
 61 FORMAT(1X,'GP1',23X,7(F7.0,5X))
    WRITE(KO,62) (PW(L,I,J),J=1,M)
 62 FORMAT(1X,'GP2',23X,7(F7.0,5X))
    WRITE(KO,63) GP3(I),GP3(I),GP3(I),GP3(I),GP3(I),GP3(I),GP3(I)
 63 FORMAT(1X,'GP3',23X,7(F7.0,5X))
    WRITE(KO,64) GP5(I),GP5(I),GP5(I),GP5(I),GP5(I),GP5(I),GP5(I)
 64 FORMAT(1X,'GP5',23X,7(F7.0,5X))
    WRITE(KO,65) GP6(I),GP6(I),GP6(I),GP6(I),GP6(I),GP6(I),GP6(I)
 65 FORMAT(1X,'GP6',23X,7(F7.0,5X))
    WRITE(KO,66) PER(I),PER(I),PER(I),PER(I),PER(I),PER(I),PER(I)
 66 FORMAT(1X,'PERSONNEL',17X,7(F7.0,5X))
    WRITE(KO,67) FOIL(I),FOIL(I),FOIL(I),FOIL(I),FOIL(I),FOIL(I),FOIL(
   1I)
 67 FORMAT(1X,'FOIL',22X,7(F7.0,5X))
    WRITE(KO,68) (STOT(L,I,J),J=1,M)
 68 FORMAT(1X,'SUB-TOTAL',22X,7(F7.0,5X))
    DO 300 K=1,MM
    WRITE(KO,69) RB(K),(WF(L,I,K,J),J=1,M)
 69 FORMAT(1X,'FUEL WT.',1X,F6.1,'NM',9X,7(F7.0,5X))
    WRITE(KO,70) RB(K),(TOT(L,I,K,J),J=1,M)
 70 FORMAT(1X,'TOTAL',F6.1,15X,7(F7.0,5X))
300 CONTINUE
    DO 301 K=1,MM
    WRITE(KO,71)DISP(I),DISP(I),DISP(I),DISP(I),DISP(I),DISP(I),DISP(I
   1)
 71 FORMAT(1X,'FULL LOAD DISPL',11X,7(F7.0,5X))
    WRITE(KO,73) RB(K),(PAYF(L,I,K,J),J=1,M)
 73 FORMAT(1X,'PAYLOAD',1X,F7.2,'NM',9X,7(F7.0,5X))
301 CONTINUE
    WRITE(KO,74) (PAYN(L,I,J),J=1,M)
 74 FORMAT(1X,'PAYLOAD NUCLEAR PLANT',5X,7(F7.0,5X))
```

```
   48 CONTINUE
   47 CONTINUE
  112 GO TO 850
  998 CONTINUE
      STOP
      END
```

```
C COMPUTERIZED SENSITIVITY ANALYSIS OF SES VARYING:
C 1.FULL LOAD DISPLACEMENT(TONS)
C 2.FULL SPEED(KTS)
C 3.RANGE(NM)
C 4.SPECIFIC PROPULSION WEIGHT(LBM/SHP)
C
C
C                            ---SPS---
C FULL LOAD DISPLACEMENT(TONS)---1000,2000,3000,5000,10000
C FULL SPEED(KTS)---40,50,60,70,80,90,100
C RANGE AT 50 KTS(NM)---1000,2000,3000,4000,5000,6000
C SPECIFIC PROPULSION WEIGHT(LBM/SHP)---5,10,20,30,50,100,120
C
C ROSENBLATT & SONS ADVANCED DESIGN WEIGHT EQUATIONS UTILIZED IN THIS MODEL
C N=NUMBER OF DISPLACEMENT INPUTS,I IS THE MATRIX INDEX
C M=NUMBER OF SPEED INPUTS,J IS THE MATRIX INDEX
C MM=NUMBER OF RANGE INPUTS, K IS THE MATRIX INDEX
C NN=NUMBER OF SPECIFIC PROPULSION WEIGHT INPUTS, L IS THE MATRIX INDEX
C MMM=INDEX OF CRUISE SPEED
C KPS=1 IMPLIES SUPERCAVITATING PROPELLERS,KPS=2 IMPLIES WATERJETS
C IF KT=2 THE PROGRAM STOPS
      DIMENSION DISP(10),PCLC(10),BC(10),PCC(10),B(10),SC(10),V(7),PC(7)
     1,SHPB(10,7),SHPL(10,7),SHPT(10,7),SPW(7),PW(7,10,7),GP1(10),GP3(10
     2),PER(10),WBS(10),WSS(10),WR(10),AUX(10,7),STOT(7,10,7),TOT(7,10,7
     3,7),PAYF(7,10,7,7),PAYN(7,10,7),WF(7,10,7,7),RB(7),WFIN(10),WAC(10
     4)
      REAL LL(10),NCREW(10),LCBC(10),LD(10,7),LLC(10),NT
      DATA KI/5/,KO/6/,NT/0.98/,HW/3.0/
C
  850 READ(KI,1)N,M,MM,NN,MMM,KPS,KT
    1 FORMAT(7I1)
      IF(KT .EQ. 2)GO TO 998
      READ(KI,111)(DISP(I),LCBC(I),PCLC(I),NCREW(I),I=1,N)
  111 FORMAT(4F10.1)
C
C
```

```
      DO  2 I=1,N
      LLC(I)=(2268.*DISP(I))**(1./3.)
      BC(I)=LLC(I)/2.
      PCC(I)=1.5*LLC(I)
      B(I)=30.+W
      B(I)=30.+BC(I)
      LL(I)=LLC(I)+.002*DISP(I)+20.
      SC(I)=LLC(I)*BC(I)
      WAC(I)=DISP(I)*2240./(LLC(I)*BC(I))**1.5
    2 CONTINUE
C
      WRITE(KO,3)
    3 FORMAT('1',42X,'PRINCIPAL DIMENSIONS AND COEFFICIENTS---SES')
      WRITE(KO,4) (DISP(I),I=1,N)
    4 FORMAT('-','FULL LOAD DISP(TONS)',5X,5(F10.3,10X))
      WRITE(KO,5) (LLC(I),I=1,N)
    5 FORMAT(1X,'CUSHION LENGTH',11X,5(F10.3,10X))
      WRITE(KO,6) (BC(I),I=1,N)
    6 FORMAT(1X,'CUSHION BEAM',13X,5(F10.3,10X))
      WRITE(KO,7) (PCC(I),I=1,N)
    7 FORMAT(1X,'CUSHION PRESSURE',9X,5(F10.3,10X))
      WRITE(KO,8) (LCBC(I),I=1,N)
    8 FORMAT(1X,'CUSH. LENGTH/CUSH. BEAM',2X,5(F10.3,10X))
      WRITE(KO,9) (PCLC(I),I=1,N)
    9 FORMAT(1X,'CUSH. PRESS./CUSH. LENGTH',5(F10.3,10X))
      WRITE(KO,10) (B(I),I=1,N)
   10 FORMAT(1X,'BEAM',21X,5(F10.3,10X))
      WRITE(KO,11) (LL(I),I=1,N)
   11 FORMAT(1X,'LENGTH',19X,5(F10.3,10X))
      WRITE(KO,12) (SC(I),I=1,N)
   12 FORMAT(1X,'CUSHION AREA',13X,5(F10.3,10X))
      WRITE(KO,771) (WAC(I),I=1,N)
  771 FORMAT(1X,'CUSHION DENSITY(LBM/FT3)',1X,5(F10.3,10X))
   13 CONTINUE
C
C
```

```
C THE NEXT SECTION WILL CALCULATE THE REQUIRED SHP FOR THE PROPULSION
C PLANT AND THE LIFT FANS FOR THE VARIOUS DISPLACEMENTS AND SPEEDS BASED
C ON L/D CURVES FOR CUSHION PRESSURE/CUSHION LENGTH=1.5,CUSHION LENGTH/
C CUSHION BEAM=2.0
C
C
      READ(KI,800) (V(J),PC(J),J=1,M)
  800 FORMAT(8F10.1)
      READ(KI,801) ((LD(I,J),J=1,M),I=1,N)
  801 FORMAT(7F10.1)
      DO 16 I=1,N
      DO 17 J=1,M
      SHPB(I,J)=DISP(I)/LD(I,J)*V(J)/325./PC(J)/NT*2240.
      Q=60.*BC(I)*HW*V(J)*1.689
      SHPL(I,J)=4.55E-05*Q*PCC(I)
      SHPT(I,J)=SHPB(I,J)+SHPL(I,J)
   17 CONTINUE
   16 CONTINUE
C
      WRITE(KO,30)
   30 FORMAT('1','FULL LOAD DISP',13X,'SPEED',12X,'L/D',10X,'PROP. COEFF
     1.',10X,'SHP')
      WRITE(KO,31) ((DISP(I),V(J),LD(I,J),PC(J),SHPT(I,J),J=1,M),I=1,N)
   31 FORMAT(4X,F7.0,16X,F5.1,8X,F8.1,12X,F4.2,12X,F8.1)
C
C DIFFERENT GROUP 1'+2+3' SPECIFIC PROPULSION WEIGHTS WILL BE UTILIZED TO
C CALCULATE SES PROPULSION WEIGHTS
C
      READ(KI,333) (SPW(L),L=1,NN)
  333 FORMAT(7F10.1)
      DO 32 L=1,NN
      DO 33 I=1,N
      DO 34 J=1,7
      PW(L,I,J)=SHPT(I,J)*SPW(L)/2240.
   34 CONTINUE
   33 CONTINUE
```

```
   32 CONTINUE
      DO 35 L=1,NN
      WRITE(KO,36)SPW(L)
   36 FORMAT('1',44X,'PROPULSION WEIGHTS---SES     (',F6.1,' LBM/SHP)')
      WRITE(KO,37)
   37 FORMAT('- FULL LOAD DISPL',10X,'SPEED',20X,'SHP',10X,'PROPUISION W
     1EIGHT')
      WRITE(KO,38) ((DISP(I),V(J),SHPT(I,J),PW(L,I,J),J=1,M),I=1,N)
   38 FORMAT(4X,F6.0,17X,F4.0,18X,F8.1,10X,F9.1)
   35 CONTINUE
C
C NEXT FOR VARIOUS FULL LOAD DISPLACEMENTS,VARIOUS SPEEDS, AND VARIOUS SPECIFIC
C PROPULSION WEIGHT,FUEL WEIGHT REQUIRED FOR A CRUISE SPEED FO 40 KNOTS
C IS CALCULATED. THEN UTILIZING THE ROSENBLATT & SONS ADVANCED DESIGN WEIGHT
C EQUATIONS, THE PAYLOAD CAN BE DETERMINED.
C
      IF (KPS .EQ. 2)GO TO 600
      DO 40 I=1,N
      DO 41 J=1,M
      GP1(I)=DISP(I)*(224.+640./DISP(I)**.0414/PCLC(I)**.776)/2240.
      GP3(I)=(804.4*(DISP(I)-1000.)**0.386+53500)/2240.
      PER(I)=(1061.*NCREW(I)+300.)/2240.
      IF(DISP(I) .GE. 2000.)GO TO 410
      WBS(I)=13.3*DISP(I)*2./LCBC(I)/2240.
      GO TO 412
  410 WBS(I)=(3.3*DISP(I)+19500)*2./LCBC(I)/2240.
  412 IF(DISP(I) .GE. 2000.)GO TO 413
      WSS(I)=14.7*DISP(I)*2.*LCBC(I)/2240.
      GO TO 414
  413 WSS(I)=(3.69*DISP(I)+20550.)*2./LCBC(I)/2240.
  414 WR(I)=(0.9*DISP(I)-550.)/2240.
      AUX(I,J)=(5500.*DISP(I)**.4+0.25*SHPT(I,J)+60700.-GP3(I)-PER(I))/2
     1240.
   41 CONTINUE
   40 CONTINUE
      GO TO 415
```

```
600 CONTINUE
    DO 416 I=1,N
    DO 417 J=1,M
    GP1(I)=DISP(I)*(224.+640./DISP(I)**.0414/PCLC(I)**.776)/2240.
    GP3(I)=(804.4*(DISP(I)-1000.)**0.386+53500.)/2240.
    PER(I)=(1061.*NCP3W(I)+300.)/2240.
    IF(DISP(I) .GE. 2000.) GO TO 418
    WBS(I)=13.3*DISP(I)*2./LCBC(I)/2240.
    GO TO 419
418 WBS(I)=(3.3*DISP(I)+19500)*2./LCBC(I)/2240.
419 IF(DISP(I) .GE. 2000.) GO TO 420
    WSS(I)=14.7*DISP(I)*2.*LCBC(I)/2240.
    GO TO 421
420 WSS(I)=(3.69*DISP(I)+20550.)*2./LCBC(I)/2240.
421 WFIN(I)=1.25*DISP(I)/100.*(DISP(I)/100.+51.2)/2240.
    AUX(I,J)=(5500.*DISP(I)**.4+0.25*SHPT(I,J)+60700.-GP3(I)-PER(I))/2
   1240.
417 CONTINUE
416 CONTINUE
415 CONTINUE
    IF (KPS .EQ. 2) GO TO 601
    DO 401 L=1,NN
    DO 402 I=1,N
    DO 403 J=1,M
    STOT(L,I,J)=GP1(I)+GP3(I)+PER(I)+WBS(I)+WSS(I)+WB(I)+AUX(I,J)+PW(I
   1,I,J)
403 CONTINUE
402 CONTINUE
401 CONTINUE
    GO TO 602
601 DO 404 L=1,NN
    DO 405 I=1,N
    DO 406 J=1,M
    STOT(L,I,J)=GP1(I)+GP3(I)+PER(I)+WBS(I)+WSS(I)+WFIN(I)+AUX(I,J)+P
   1W(L,I,J)
406 CONTINUE
```

```
405 CONTINUE
404 CONTINUE
602 CONTINUE
    READ(KI,999) (RB(K),K=1,MM)
999 FORMAT(6F10.1)
    DO 750 L=1,NN
    DO 751 I=1,N
    DO 752 K=1,MM
    DO 753 J=1,M
    X=SHPT(I,MMM)/SHPT(I,J)
    GO TO (505,505,520,520,550,332,332),L
505 IF(X .GT. 0.14) GO TO 506
    SFC=.075/X**.866
    GO TO 802
506 SFC=.410/X**.185
    GO TO 802
520 IF(X .GT. 0.16) GO TO 507
    SFC=.57/X**.1
    GO TO 802
507 SFC=.372/X**(1./3.)
    GO TO 802
550 SFC=0.34/X**.0745
    GO TO 802
332 SFC=0.32/X**.0786
    GO TO 802
802 CONTINUE
    Y=EXP(RB(K)*SFC*SHPT(I,MMM)/(2240.*DISP(I)*V(MMM)))
    WF(L,I,K,J)=1.108*DISP(I)*(Y-1.)/Y
753 CONTINUE
752 CONTINUE
751 CONTINUE
750 CONTINUE
    DO 43 L=1,NN
    DO 44 I=1,N
    DO 45 K=1,MM
    DO 46 J=1,M
```

```
      TOT(L,I,K,J)=STOT(L,I,J)+WP(L,I,K,J)
      PAYP(L,I,K,J)=DISP(I)-TOT(L,I,K,J)
      PAYN(L,I,J)=DISP(I)-STOT(L,I,J)
   46 CONTINUE
   45 CONTINUE
   44 CONTINUE
   43 CONTINUE
      DO 47 L=1,NN
      DO 48 I=1,N
      WRITE(KO,450)SPW(L)
  450 FORMAT('1',40X,'FUEL WEIGHT AND PAYLOAD FOR SES        (',F6.1,'LBM/
     1SHP)')
      WRITE(KO,60)DISP(I),(V(J),J=1,M)
   60 FORMAT('- FULL LOAD DISPL=',F6.0,5X,7(F4.0,'KTS',5X))
      WRITE(KO,61) GP1(I),GP1(I),GP1(I),GP1(I),GP1(I),GP1(I),GP1(I)
   61 FORMAT(1X,'SP1',23X,7(F7.0,5X))
      WRITE(KO,62) (PW(L,I,J),J=1,M)
   62 FORMAT(1X,'GP2',23X,7(F7.0,5X))
      WRITE(KO,63) GP3(I),GP3(I),GP3(I),GP3(I),GP3(I),GP3(I),GP3(I)
   63 FORMAT(1X,'GP3',23X,7(F7.0,5X))
      WRITE(KO,64) WBS(I),WBS(I),WBS(I),WBS(I),WBS(I),WBS(I),WBS(I)
   64 FORMAT(1X,'WBS',23X,7(F7.0,5X))
      WRITE(KO,65) WSS(I),WSS(I),WSS(I),WSS(I),WSS(I),WSS(I),WSS(I)
   65 FORMAT(1X,'WSS',23X,7(F7.0,5X))
      IF(KPS .EQ. 2) GO TO 690
      WRITE(KO,899)WR(I),WR(I),WR(I),WR(I),WR(I),WR(I),WR(I)
  899 FORMAT(1X,'WR',24X,7(F7.0,5X))
      GO TO 691
  690 WRITE(KO,89)WFIN(I),WFIN(I),WFIN(I),WFIN(I),WFIN(I),WFIN(I),WFIN(I
     1)
   89 FORMAT(1X,'WFIN',22X,7(F7.0,5X))
  691 WRITE(KO,901) (AUX(I,J),J=1,M)
  901 FORMAT(1X,'AUX',23X,7(F7.0,5X))
      WRITE(KO,66)PER(I),PER(I),PER(I),PER(I),PER(I),PER(I),PER(I)
   66 FORMAT(1X,'PERSONNEL',17X,7(F7.0,5X))
      WRITE(KO,68) (STOT(L,I,J),J=1,M)
```

```
 68 FORMAT(1X,'SUB-TOTAL',17X,7(F7.0,5X))
    DO 300 K=1,MM
    WRITE(KO,69)RB(K),(WF(L,I,K,J),J=1,M)
 69 FORMAT(1X,'FUEL WT.',1X,F6.0,'NM',9X,7(F7.0,5X))
    WRITE(KO,70) RB(K),(TOT(L,I,K,J),J=1,M)
 70 FORMAT(1X,'TOTAL',F6.0,15X,7(F7.0,5X))
300 CONTINUE
    DO 301 K=1,MM
    WRITE(KO,71)DISP(I),DISP(I),DISP(I),DISP(I),DISP(I),DISP(I),DISP(I
   1)
 71 FORMAT(1X,'FULL LOAD DISPL',11X,7(F7.0,5X))
    WRITE(KO,73) RB(K),(PAYF(L,I,K,J),J=1,M)
 73 FORMAT(1X,'PAYLOAD',1X,F7.0,'NM',9X,7(F7.0,5X))
301 CONTINUE
    WRITE(KO,74)(PAYN(L,I,J),J=1,M)
 74 FORMAT(1X,'PAYLOAD NUCLEAR PLANT',5X,7(F7.0,5X))
 48 CONTINUE
 47 CONTINUE
112 GO TO 850
998 CONTINUE
    STOP
    END
```